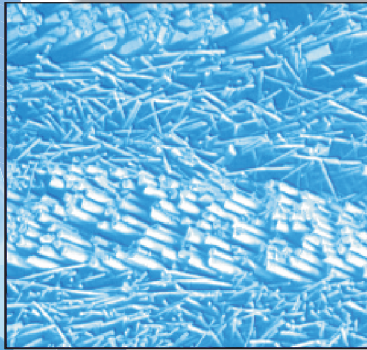
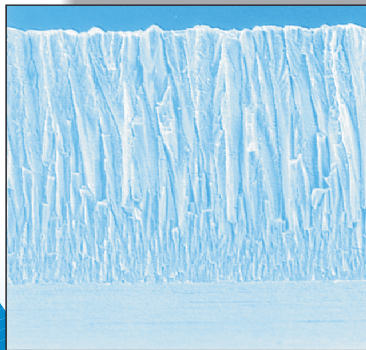


Advanced Ceramics Technology Roadmap

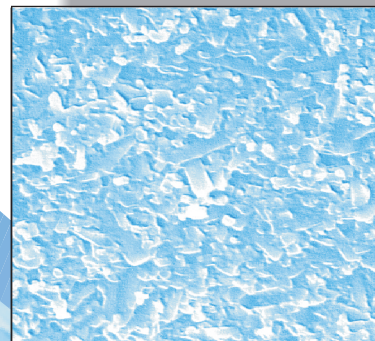
— Charting Our Course



Ceramic Matrix Composites



Ceramic Coating Systems



Monolithic Ceramics

About This Roadmap

The United States Advanced Ceramics Association and the U.S. Department of Energy co-sponsored a workshop to bring together a broad range of ceramic manufacturers and end-user companies. This roadmap, which summarizes the insights of those 40 workshop participants, sets forth the research, development and demonstrations needed for improving advanced ceramics. Achievement of the RD&D will significantly improve energy efficiency and productivity in many industries and help them reach their performance targets for 2020. Recognition and appreciation is extended to the workshop participants who volunteered their personal time to contribute valuable expertise and perspective.

The workshop was organized and facilitated by Jack Eisenhower, Keith Jamison, and Melissa Eichner of Energetics, Incorporated. This roadmap was prepared by Melissa Eichner of Energetics, Incorporated and David W. Richerson of Richerson and Associates.

Cover photographs are provided courtesy of the following companies: Dow Corning Corporation; General Electric Company; Honeywell Advanced Composites Inc.; Kyocera Industrial Ceramics Corporation; McDermott Technologies, Inc.; Saint-Gobain Ceramics & Plastics, Inc.; and Solar Turbines, Inc. The photograph on page 1 is provided courtesy of Saint-Gobain Advanced Ceramics–CERBEC.

Comments or question regarding this roadmap should be directed to Robert Mauro, Executive Director of the United States Advanced Ceramics Association at the following: 1800 M Street, NW, Suite 300, Washington, DC 20036-5802; telephone 202-293-6253; fax 202-223-5537; or rmauro@ttcorp.com.

Advanced Ceramics Technology Roadmap

— Charting Our Course

*Priority Research, Development and Demonstration
Needs to Advance Monolithic Ceramics, Ceramic
Matrix Composites, and Ceramic Coating Systems*

December 2000

Sponsored by
**United States Advanced Ceramic Association
U.S. Department of Energy**

Prepared by
Energetics, Incorporated
and
Richerson and Associates

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Advanced Ceramics Technology Roadmap – Charting Our Course

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1. Executive Summary and Introduction

Advanced ceramics are wear-resistant, corrosion-resistant, lightweight, and more stable than other materials in high-temperature environments. Because of this combination of properties, advanced ceramics have an especially high potential to resolve a wide number of today's material challenges in process industries, power generation, aerospace, transportation, and military applications. Such applications are vital to maintaining global competitiveness, decreasing energy consumption, and minimizing pollution.

In the past three decades, breakthroughs in advanced ceramics have enabled significant new technology capabilities that are now having far-reaching impacts on the U.S. economy and society. For example, ceramic catalytic converters are responsible for reducing automobile emissions and long-life bearings are used in a wide range of applications to improve performance and reduce friction. The U.S. market value of advanced ceramics was nearly \$7.5 billion in 1998, and this value is projected to grow to \$11 billion by 2003.¹ More importantly, ceramics leverage much larger economic and social benefits. Catalytic converters alone enable a \$36 billion pollution control business each year and have reduced air pollution by 1.5 billion tons since 1975.² The technological breakthroughs that make this possible are the result of sustained RD&D investment by industry and government.

Silicon Nitride Ceramic Bearings and Components



RD&D began in 1972, and bearings reached the market in 1988.

- 3-10 times life of metal bearings
- 80% lower friction
- 15-20% lower energy consumption

Advanced Structural Ceramics Have the Potential to Solve Critical Challenges in Demanding Applications

| Processing and Manufacturing Industries | Power Generation, Aerospace, and Transportation | Military |
|--|--|---|
| <ul style="list-style-type: none">• Extend equipment life• Decrease emissions• Decrease maintenance• Increase energy efficiency• Increase recycling, including process chemicals and water | <ul style="list-style-type: none">• Extend equipment life• Decrease emissions• Increase specific power• Decrease fuel use• Reduce cost• Reduce weight | <ul style="list-style-type: none">• Expand capabilities of weapons and detection systems• Decrease vulnerability• Increase reliability• Reduce cost of equipment, systems and deployment |

¹ Source: Business Communications Co., Inc.

² Source: Corning, Incorporated, 1999.

Despite these successes, advanced ceramics are only used in a small percentage of applications that could benefit from their capabilities. Many OEMs and end-users are reluctant to try them because of concerns about reliability, higher costs compared to competing materials, insufficient design and test experience, and, in some cases, inadequate properties to meet the needs of demanding applications. Today, the advanced ceramics industry is faced with an enormous opportunity as numerous sectors search for new or improved materials to resolve their technological challenges and improve competitiveness.

To realize the vast commercial potential, the advanced ceramics industry must address the needs of original equipment manufacturers (OEM) and end-users. Specifically, RD&D is needed to optimize material properties to meet the reliability requirements of specific applications, successfully demonstrate reliability through long-term end-user field tests, and gain fabrication efficiencies to allow market entry. With such continued development, the advanced ceramics market could grow significantly and leverage far more in economic benefits to end-users through maintenance reduction, energy efficiency, pollution reduction, and increased equipment life.

To respond to OEM/end-user opportunities, the U.S. Advanced Ceramics Association (USACA) has brought together the advanced ceramics industry to chart a course for the future designed to meet the diverse material needs of important U.S. sectors over the next 20 years. This roadmap is the first step in reaching consensus on priority needs and preparing a long-range RD&D plan for advanced ceramics. The ideas presented in the following pages summarize the priorities identified at an *Advanced Ceramics Technology Roadmap Workshop*, which was held September 22–23, 1999. 40 participants representing ceramic manufacturers, OEMs, research laboratories, and the government attended the workshop, which was sponsored by USACA and the Department of Energy’s Office of Industrial Technologies and the Office of Power Technologies. A workshop agenda and a list of participants are presented in Appendix A and B, respectively.

A 2020 Vision for Advanced Structural Ceramics

The ceramics industry has established an ambitious vision for advanced ceramics aimed at providing maximum benefit to OEMs and end-users (see Appendix C). In 2020, advanced ceramics will be cost-effective, preferred materials in demanding applications of industry, power generation, aerospace, transportation, military, and consumer products. Design methods, property testing standards, and property databases will be available so that a team (designer, supplier, end-user) can select a ceramic that will reliably meet the application requirements and provide benefits superior to alternate materials (metals, polymers). Ceramics will be fabricated into complex and large shapes with minimum development time and minimum defects. NDE techniques will be able to detect small critical defects and bolster production efficiencies. End-users will have experience and confidence using ceramics.

Vision for Advanced Structural Ceramics

By 2020, advanced structural ceramics are cost-effective preferred materials that exceed the performance of other materials due to reliability, high-temperature capability, and other unique properties. Products are initially designed for ceramic materials with confidence, using established standards and design tools. Automation and other advanced fabrication processes optimize cycle times and yield, ensure predictable and controllable production, and eliminate the need for post-process inspection.

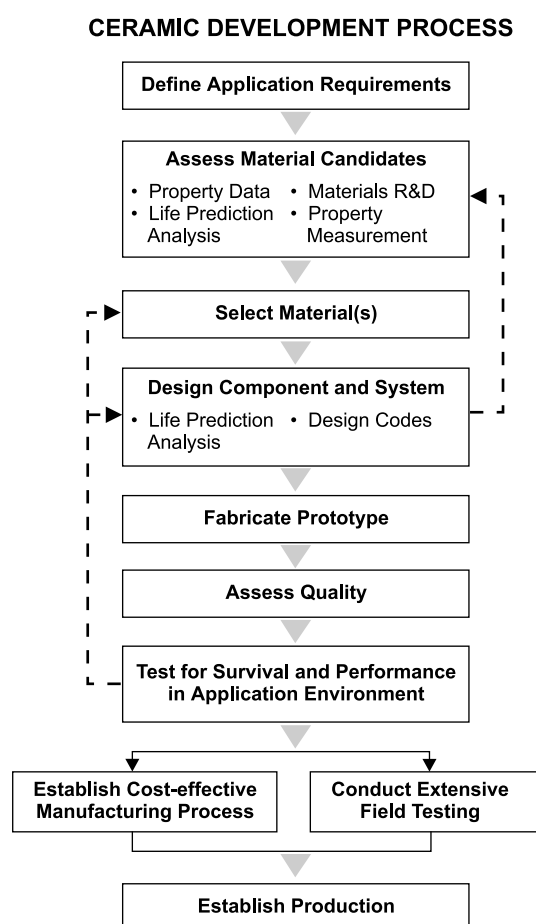
RD&D Needed to Meet OEM and End-user Requirements

The RD&D required for three major classes of ceramics – monolithic ceramics, ceramic matrix composites (CMCs), and ceramic coating systems – are presented in Exhibits 1, 2 and 3, respectively. These exhibits identify the priority technical challenges that must be met to satisfy OEM/end-user requirements and the RD&D needed to address these challenges. The exhibits will be used to communicate consensus research needs throughout the advanced ceramics industry so that collaborative projects may begin. In addition, they will be used to fortify support from end-use sectors that can use advanced ceramics to achieve their own visions. Successful achievement of the RD&D is expected to have significant near-term and long-term market impacts in process industries, power generation, transportation, aerospace, military, and other applications. Detailed analyses of the priority research needs for monolithic ceramics, CMCs, ceramic coating systems, and issues common to all three advanced structural ceramics are presented in sections 2, 3, 4, and 5, respectively. Comprehensive lists of RD&D needs from the workshop are presented in Appendices D, E, and F.

Conclusions

Developing a ceramic component for a specific application requires eight distinct steps that are outlined below. Reducing the development time and the number of iterations compared to competing materials is key to ceramics' commercial success. Improving advanced ceramics to meet the expectations of end-users will require an iterative RD&D approach that considers these steps simultaneously:

1. Define the requirements (temperature, pressure, etc.) in a specific application or group of similar applications
2. Assess the suitability of existing ceramic-based materials and identify where improvements are needed
3. Select one or more ceramic material candidates
4. Design a prototype component and system
5. Fabricate a prototype
6. Assess the quality of the prototype component
7. Evaluate the prototype in simulated and real environments, including long-term field testing
8. Develop and optimize a viable fabrication process for production



The RD&D needs address both the near-term and long-term barriers to meeting end-user requirements. In the near-term, efforts are needed to grow the business application by application. Solving the remaining critical challenges in emerging applications and in new target applications can achieve this

growth. Long-term efforts are needed to reach desired manufacturing efficiencies and performance profiles. Gaining fundamental understanding and developing enabling methods that can be applied to solve unique and crosscutting problems in numerous applications can achieve these requirements.

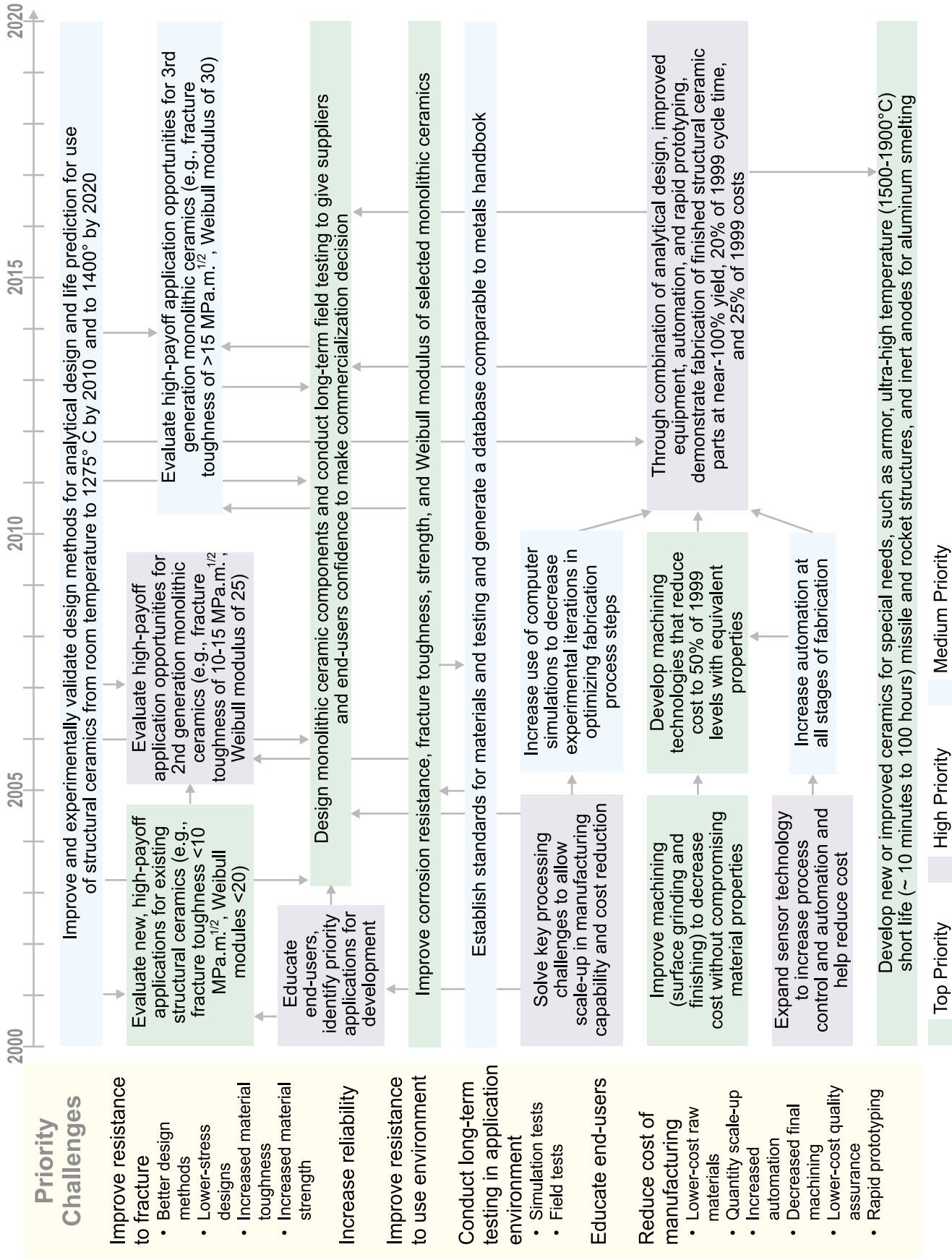
The breakthroughs needed to realize the full benefits of advanced structural ceramics will require a significant and sustained research effort over the next two decades. This effort will require dedication from industry, academia, government and national laboratories and will build on past achievements to solve problems that currently prohibit the use of ceramics in specific applications. Although the research needed is high-risk, comparable breakthroughs that have already been achieved in advanced ceramics lend credibility to the research effort. Advanced ceramics have the potential to revolutionize sectors throughout the economy.

RD&D is needed in the following interrelated areas:

- **Materials Database** – generate data to use in material selection and improvement and to support analytical design and life prediction
- **Design and Life Prediction** – improve methods and analytical tools to allow efficient analytical component design (replace inefficient “build and break” iterative methods)
- **Non-Destructive Evaluation** – improve methods and equipment for low-cost component inspection and quality assurance
- **Fabrication Optimization** – improve the fabrication process to increase material reliability, improve manufacturing scale-up capability, and reduce costs
- **Demonstrations** – verify component viability through long-life testing and testing in the end-use environment

EXHIBIT 1. MONOLITHIC CERAMICS RD&D PRIORITIES

RD&D Needed to Meet End-User Requirements



Status: Monolithic ceramics are in limited use today, but they could provide benefits in a wider range of applications.

RD&D Priorities:

➤ **Component field tests are needed to demonstrate that existing monolithic ceramics can increase component life with equivalent or better performance and reliability than metal alloys in use.** The advanced ceramics industry must educate end-users regarding the capability and successes of existing structural monolithic ceramics so end-users can accurately assess the value of advanced ceramics in specific component applications and understand the need for iterations of design and field-testing. Research is also needed to improve component design, fabrication, and evaluations (pre-test through post-test) at field test sites so end-users will use ceramics with confidence over the next 3 to 10 years. As design methods and tools improve and monolithic ceramics with higher strength, toughness, and corrosion resistance are developed, applications of increased severity can be addressed over the next 5 to 20 years.

➤ **RD&D must help reduce the cost of advanced ceramics.** Unit cost of monolithic ceramics is high because of low-volume production, high-cost diamond grinding, and high-cost inspection to assure reliability. Areas to target for cost reduction include fabrication steps (especially improved sensors, automation, and optimization of process equipment design), machining, and scale-up to the level required for suppliers and end-users to make full-production commercialization decisions. Eliminating fabrication cost and scale issues are keys to commercialization success.

➤ **Fundamental and applied RD&D is needed to increase reliability and to meet the needs of applications with environments that are too severe for present materials.** RD&D is needed to understand the degradation and failure mechanisms in simulated and real application environments and to improve material properties (especially fracture toughness, oxidation/corrosion resistance, and temperature capability). These capabilities are needed to achieve the lifetime and reliability demanded by the OEMs and end-users. Extensive property testing and microstructural/microchemical analysis will guide efforts to improve performance and generate a critical database. Efforts will focus on linking RD&D to end-user driven needs including improvements in key properties as well as diverse special needs such as high temperature ceramics for gas turbine engines, a non-oxidizing (inert) anode for aluminum smelting, and next-generation armor.

Market Impact:

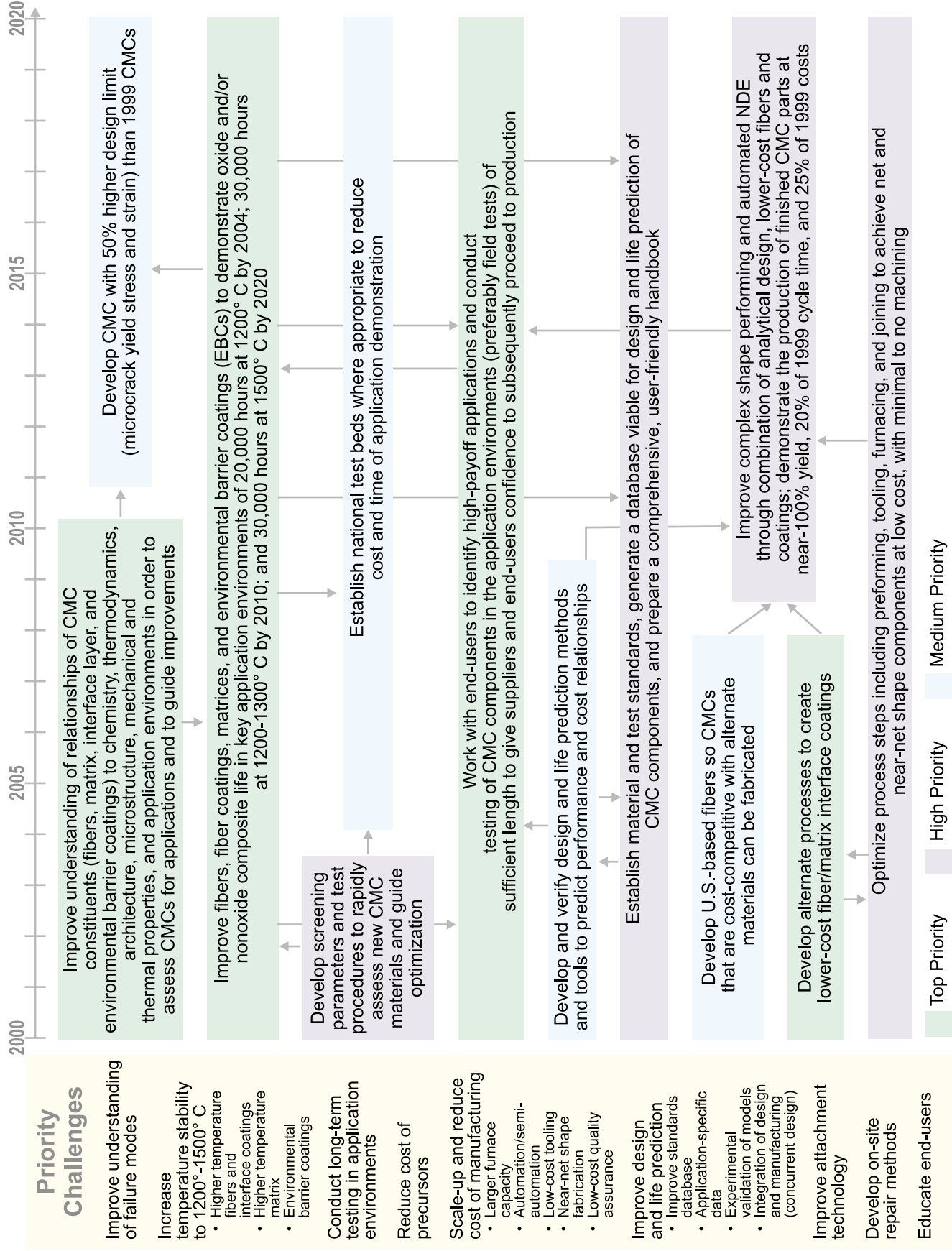
Near-term RD&D on monolithic ceramics will provide major benefits to process industries by promoting the use of ceramics with superior wear resistance, oxidation/corrosion resistance, and higher temperature capability to replace metals. As materials improvements are achieved, the benefits will extend to power generation, aerospace, and military sectors. As manufacturing costs decrease and reliability increases, the benefits will extend to the transportation sector as well.

Monolithic ceramics refers to a broad category of ceramics that often includes the following attributes: a stand-alone part instead of a coating; little or no porosity; a polycrystalline microstructure without a reinforcing phase added during fabrication; and fracture susceptibility at room temperature in a brittle mode.

Examples of monolithic ceramics include dense forms of aluminum oxide, silicon nitride, silicon carbide, and transformation-toughened zirconia.

EXHIBIT 2. CERAMIC MATRIX COMPOSITES RD&D PRIORITIES

RD&D Needed to Meet End-User Requirements



Status: CMC technology is still in an early stage of development, with many challenges that must be addressed to make CMCs available to end-users.

RD&D Priorities:

- **RD&D is needed to understand the interactions of the composite constituents (fibers, matrix, interface coatings, surface coatings) with one another and with the application environments.** This will require iterations of composition selection, fabrication, testing, and post-test evaluation to assess performance. These material development and characterization efforts will need to be closely linked to improving design and life prediction tools and establishing standards and databases.
- **Increasing CMC lifetime is a top priority.** Research efforts will focus on progressively increasing the temperature capability, life, and ultimately the design limit (the stress to which the CMC can be exposed). These priorities will require focused RD&D on fibers, fiber coatings, matrix chemistry, and environmental barrier coatings (EBCs) as well as fabrication and testing. Establishing facilities for simulated and accelerated testing and partnerships with end-users for field-testing are critical to achieving success.
- **CMC RD&D must help resolve cost issues.** Currently, CMCs are considered for only a limited number of premium applications because of the high costs of raw materials, fabrication, and inspection. Reducing costs will expand opportunities in applications that can benefit from longer life and higher reliability than metals and monolithic ceramics. Research should help reduce the cost of precursors (especially fibers), increase the scale of fabrication, achieve near-net-shape fabrication, implement process automation or semi-automation, and minimize or automate quality assurance inspections.

Market Impact:

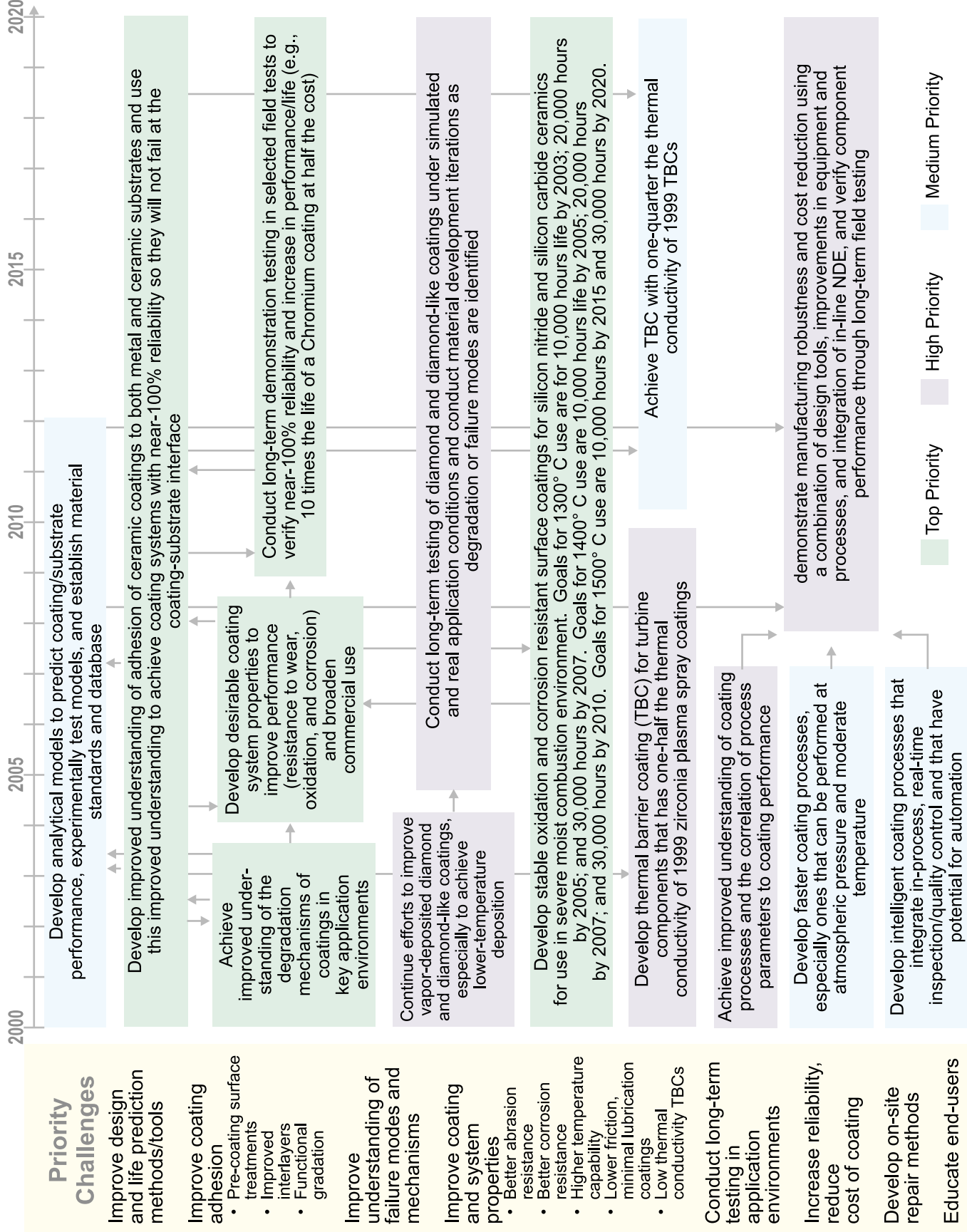
CMC development, though high-risk, could fulfill urgent needs leading to high payoffs in the near-term for industrial turbines, pollution control, and process industries, and in the mid-term for military and aerospace applications. The potential of CMCs to significantly increase the efficiency of energy use and reduce emissions of greenhouse gases is especially high.

Ceramic Matrix Composites (CMCs) are ceramic materials that incorporate discontinuous or continuous reinforcements (particles, whiskers, fibers) into a ceramic matrix to create new materials with superior properties.

Examples of CMCs include silicon carbide fibers in silicon carbide matrix and aluminum oxide fibers in aluminum oxide matrix.

EXHIBIT 3. CERAMIC COATING SYSTEMS RD&D PRIORITIES

RD&D Needed to Meet End-User Requirements



Status: Ceramic coating systems are in wide use today. Improved coating systems and coating properties would expand use in many sectors.

RD&D Priorities:

➤ **RD&D should focus on improving adhesion between the coating and substrate to provide longer life and higher equipment reliability; developing a better understanding of the mode and mechanisms of coating degradation in application environments; improving coating material properties to resist degradation mechanisms; and optimizing coating processes to minimize cost.** Such research will require iterations of chemical composition modifications, deposition, exposure to simulated and real application environments, and microstructure/microchemical evaluation.

➤ **Improved vapor-phase deposited diamond and diamond-like coatings are needed.** These coatings are relatively new technologies that have the potential to dramatically increase wear resistance and extend equipment life. RD&D should help decrease the cost of vapor-phase deposition, decrease deposition temperature so diamond (or diamond-like) coatings can be applied to lower-temperature substrates (e.g., mild steel and non-ferrous alloys), and evaluate performance and degradation mechanism in real application field tests.

➤ **Thermal barrier coatings (TBCs) must be improved.** TBCs are used to allow engines to operate at increased temperatures, substantially increasing power per unit volume and reducing fuel consumption. RD&D and application evaluations are needed to increase the life of the TBC system to greater than 20,000 hours, increase temperature capability, and further decrease thermal conductivity to keep the underlying metal cooler.

➤ **Improved coatings are needed for fibers used in CMCs fabrication and for protective surfaces applied to CMCs and monolithic ceramic components such as environmental barrier coatings (EBCs).** These priority needs are addressed in the CMC and monolithic ceramic sections, respectively.

➤ **Specialized ceramic coating technologies are needed.** Research is needed for modified surfaces of refractories (in all of the processing industries), next-generation space shuttle surface protection, space structure coatings, functionally graded coatings, and coatings with combined optical and structural or electrical and structural functions. Coating system RD&D will also improve design and life prediction methods and tools and develop on-site repair methods.

Market Impact:

Benefits will accrue to all market sectors with technology spinning off to products within three years and accelerating through the year 2020.

Ceramic coatings are typically a thin layer of ceramic deposited on metal or ceramic to impart improved resistance to corrosion, wear, or temperature. Underlying metal substrates can carry the structural load and minimize the likelihood of catastrophic failure. Coatings deposited onto a substrate conform to the shape of the substrate, allowing complex shaped parts to be fabricated with the benefits of a ceramic at relatively low cost and without the costs associated with fabricating the whole part from a ceramic. Coatings are also used on monolithic ceramics and CMCs to obtain required performance characteristics.

Examples of coating techniques include plasma spray, flame spray, high velocity oxy-fuel deposition, electron beam physical vapor deposition, and chemical vapor deposition.

2. Monolithic Ceramics – Challenges and Needs

Monolithic describes a broad category of ceramics that is difficult to define succinctly. In this roadmap, ceramics are monolithic if they exhibit the following attributes:

- Fabricated as a stand-alone part, rather than applied as a coating
- Comprised of a polycrystalline microstructure without a reinforcing phase added during fabrication
- Fracture at room temperature in a brittle mode

Based on these criteria, two important ceramics, silicon nitride and transformation-toughened zirconium oxide, are classified as monolithic ceramics, despite the composite-like microstructures that form during their fabrication processes. Other examples of monolithic ceramics with potential for structural applications include silicon carbide, aluminum oxide, aluminum nitride, mullite, cordierite, zirconium diboride, zirconium carbide, and titanium diboride.

When end users consider a monolithic ceramic, four potential barriers are often cited: inadequate resistance to fracture, inadequate resistance to the use environment, inadequate or uncertain reliability, and cost effectiveness. Exhibit 4 lists the challenges and the priority RD&D needs to address the challenges. The challenges and RD&D needs are discussed below. Note: several key monolithic ceramic challenges are addressed in Section 5 on RD&D needs common to monolithic, composite, and coating ceramics. These efforts need to be integrated with relevant material development, database generation, fabrication, and demonstration activities.

Exhibit 4. Priority RD&D Needs in Monolithic Ceramics to Address Key Challenges Faced by Ceramic Manufacturers and End Users

| <i>Key Challenges for Monolithic Ceramics</i> | <i>Priority RD&D Needs to Address the Challenge</i> |
|--|---|
| Improve resistance to fracture | <ul style="list-style-type: none">• Increased material toughness• Increased material strength• Better design methods/practices• Lower stress designs |
| Improve resistance to the use environment (e.g., oxidation, corrosion) | <ul style="list-style-type: none">• Improved material chemical stability• Protective coatings• Functional gradient construction• Improved resistance to contact stress |
| Increase reliability | <ul style="list-style-type: none">• Reduced material variability through improved fabrication process control |
| Reduce the cost of manufacturing | <ul style="list-style-type: none">• Lower-cost powders/precursors• Quantity scale-up• Increased automation• Decreased final machining• Lower-cost quality assurance• Rapid prototyping integrated into manufacturing |

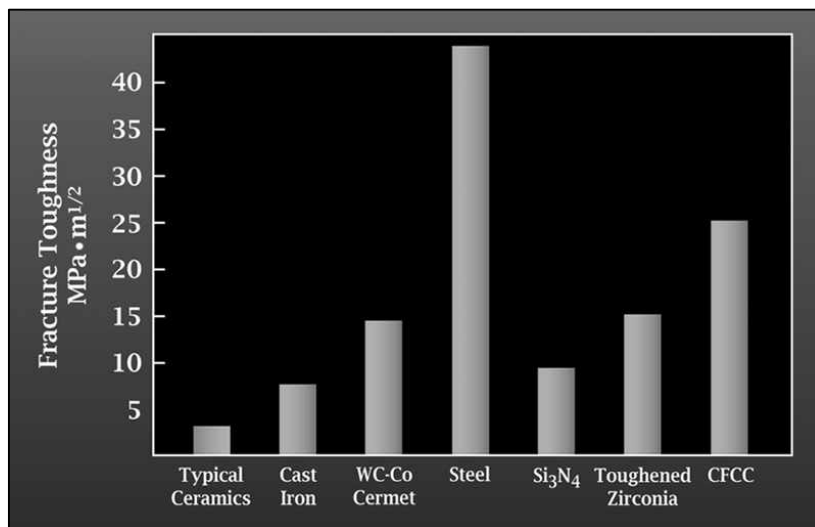
Technology Challenge: Improve Resistance to Fracture

The brittle fracture behavior of monolithic ceramic components is a major concern to end-users, especially fear of catastrophic fracture. While major advancements have been achieved, further improvement is needed to develop fracture-resistance capabilities comparable to alternative materials. For some applications, monolithic ceramics exist with adequate fracture resistance to meet end-user requirements, but end users are not aware of the material capabilities or are not willing to try them.

RD&D Priority

Increased Material Toughness. Toughness is the resistance of a material to propagation of a crack through the material. Traditional monolithic ceramics have relatively low resistance; a stress applied to the ceramic concentrates at the tip of the crack, easily driving the crack completely through to cause fracture. In contrast, a ductile metal deforms at the tip of the crack, spreading the stress over a larger volume. For example, traditional polycrystalline monolithic ceramics have fracture toughness ranging from 2 to 4 MPa.m^{1/2}, while ductile metals have values typically well above 40 MPa.m^{1/2}.

Since the 1970s, the toughness of monolithic ceramics has increased significantly, primarily through understanding the interrelationships of toughness, microstructure, and the fabrication process. Toughness values of nearly 10 MPa.m^{1/2} have been achieved for special silicon nitride compositions and nearly 15 MPa.m^{1/2} for some transformation-toughened zirconium



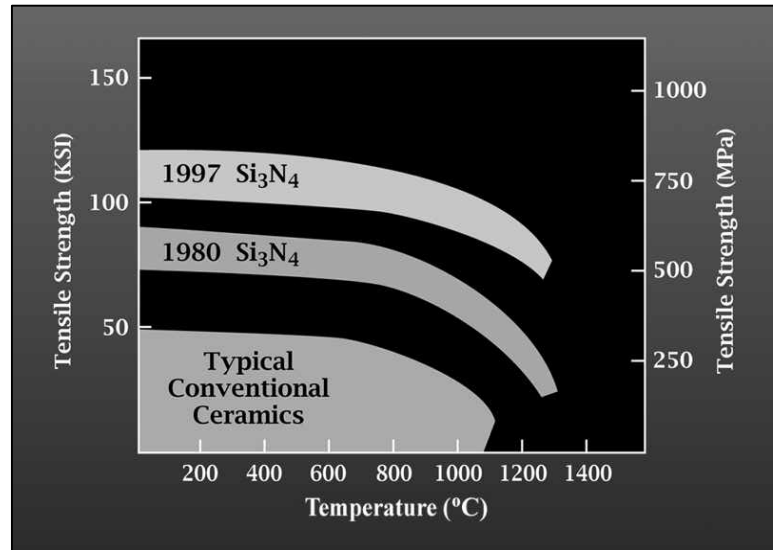
oxide compositions. Even though improved toughness does not prevent brittle fracture, these ceramics are much more resistant to handling, impact, thermal shock and other application abuses that limited the use of traditional ceramics. Improved toughness significantly contributed to the successful use of silicon nitride in cutting tools, bearings, heat engines, and industrial wear-resistant parts and of transformation-toughened zirconia for wire-drawing, aluminum can manufacturing, papermaking tooling, and many other industrial wear-resistant parts.

Even with the improvements achieved, monolithic ceramics are not considered for many eligible applications. In some applications, they are still inadequate. *RD&D is needed to increase fracture toughness to help alleviate end-user reluctance and meet ever-increasing demands of new applications.* The target of 20 MPa.m^{1/2} in 2020 is a difficult challenge that will require focused long-term basic RD&D.

Increased Material Strength. Strength is a measurement of the load (or stress) at which a crack starts in a ceramic, as opposed to toughness that is a measurement of the resistance of the ceramic to the extension of the crack. Both are related and together determine the fracture behavior of a

material. The strength of monolithic ceramics has improved considerably. Prior to 1960, 290 MPa (20,000 psi) was considered high strength for a ceramic; now ceramics are produced with strength greater than 500 MPa. Silicon nitride materials, for example, are now available with average room temperature strength approaching 1000 MPa and with strength at 1200°C of around 700 MPa. To put these values in perspective, a 2.5-cm cross section of a 1000 MPa material can lift the weight of fifty 3000-pound automobiles.

Historically, ceramics have had a wide strength distribution. For example, an early 1970s silicon nitride had an average strength of 700 MPa, but a maximum of 900 MPa and a minimum of 400 MPa. In statistical terms, this material had a Weibull modulus below 8. The Weibull modulus for metals are typically greater than 40, so designers and end-users were suspect of ceramic reliability. At present, Weibull moduli between 15 and 20 have been achieved for silicon nitride materials, but not



consistently across batches and manufactured shapes. *Continued research is needed to increase the strength, especially to improve the uniformity of strength within a ceramic part and from part-to-part, in order to increase the Weibull modulus to >30.*

Better Design Methods/Practices. For structural applications, monolithic ceramics require a different design method than metals. Because of their brittle fracture mode, ceramics require a probabilistic design method that simultaneously accounts for the stress distribution in a ceramic component and for the statistical distribution of strength-limiting defects in the ceramic microstructure. Tremendous progress has been made to establish a probabilistic design methodology. This is used for ceramic component design in gas turbine engines and other heat engine components. However, it has not been widely adopted or adapted for industrial applications. *To improve design methods, RD&D is needed to: compile a materials-allowable design manual and database handbook that can be readily used by industry comparable to metals handbooks; incorporate probabilistic design into user-friendly design software; develop a concurrent engineering and design methodology that encourages designing for manufacturability; and establish a center for advanced structural ceramics design and tool development.*

Lower Stress Designs. Historically, evaluating a ceramic for an application involved duplicating the metal part, usually without success. Ceramics designs must keep the mechanical and thermal stresses within reasonable limits. Design tools and boundary conditions data are currently inadequate to accurately predict the stress distribution. As a result, multiple iteration of design and testing are required. *RD&D are needed to improve the iterative efforts between design and testing to achieve low-stress, high-reliability ceramic component designs.* High-risk, high-payoff components would benefit from this research.

Technology Challenge: Improved Resistance to the Use Environment

Components are used in severe stress, temperature, corrosion, and wear environments (e.g., in processing industries, power generation systems, and heat engines). Improving strength and toughness can provide resistance to stress and wear, but will not ensure resistance to corrosion and oxidation, especially at high temperature. Applications involving combustion are especially severe, particularly when ash particles and molten salts are present. Water vapor and operation pressures higher than normal atmosphere can dramatically reduce material resistance to attack.

RD&D Priority

Improved Material Chemical Stability. Stability in the use environment also is a key issue for extending equipment life and reducing maintenance in many applications. Continuing research is needed to understand the fundamentals of thermochemical stability of key monolithic ceramic materials and to develop ceramics with improved chemical stability. Testing in actual use environments is essential. For example, silicon nitride compositions developed during the 1990s survived in laboratory furnace tests for thousands of hours at temperatures up to 1400° C under stress levels comparable to applications such as turbine engines. However, when these materials were tested in actual engines under pressure, flowing gases, and moist atmospheres, they exhibited much lower chemical stability and unacceptable oxidation recession rates. *Existing, new, and modified chemical compositions in specific application environments will need to be considered and evaluated through iterations of synthesis, exposure in the use environment, and post-exposure testing/analysis. Also, RD&D is needed with broad applicability such as increasing the oxidation resistance of non-oxide ceramics.*

Protective Coatings. Coatings on monolithic ceramics may be a viable approach to solve current problems of high temperature oxidation and contact stress, especially impact. Non-oxide ceramics have relatively low thermal expansion and most oxides have moderate-to-high thermal expansion; consequently, high stresses result at the coating interface. *Focused RD&D on protective coatings is needed to solve the problems associated with high-temperature oxidation and contact stress.* Research is needed for applying an oxide coating onto a non-oxide ceramic such as silicon nitride or silicon carbide.

Functional Gradient Ceramics. To provide environmental resistance, a monolithic ceramic could be developed with a graded composition or microstructure that provides optimum resistance to the application environment at and near the surface and optimum structural properties in the interior to resist mechanical and thermal stresses. *Research is needed to fabricate a functionally graded ceramic such as with the use of new rapid prototyping technology.*

Improved Resistance to Contact Stress. Ceramics often fail where they are attached to another material or where they contact another material during use. Sliding contact and impact both are known to cause high local stress, causing damage or failure. Many failures in structural ceramic components have been linked to contact stress and inadequate design to tolerate the contact stress or inadequate material strength and toughness. Contact stress is not often recognized as a design criterion. Instead, it is addressed after the ceramic part fails. *An integrated research approach is needed to reduce contact stress, including better analytical design tools, improved understanding of ceramic material and component limits, improved materials and design, and education of designers and end-users.*

Technology Challenge: Increase Reliability

The RD&D needs discussed above will increase the reliability of monolithic ceramics. Additional research is needed to increase the reliability of the fabrication process.

RD&D Priority

Reduced Material Variability Through Improved Fabrication Process Control. Material variability can have far reaching impact on the effectiveness of the design and fabrication process. *RD&D is needed to reduce the variability of key monolithic ceramics.* Improving process control in particular can decrease the variability and minimize the chance of a worse-than-average defect. *RD&D is needed to refine process control capability for fabrication.* Significant improvements have already been achieved for some silicon nitride materials (Weibull modulus increased from less than 10 to around 20), providing a model for improving other ceramics and for further improvement of silicon nitride ceramics.

Technology Challenge: Reduced Cost of Manufacturing

Advanced monolithic ceramics such as silicon nitride, silicon carbide, and transformation toughened zirconia have demonstrated superior performance during evaluations in severe applications, yet they were not selected because of cost.

RD&D Priority

Lower-Cost Powders/Precursors. Monolithic ceramics are typically fabricated by compacting a powder or mixture of powders and other precursors and then firing them at high temperature to consolidate the powder into a solid ceramic. Highly refined powders and precursors are typically required that are expensive until large-volume production is reached. Powder suppliers must either charge high prices or run at a loss until enough end-use applications exist for large-volume production.

Developing a U.S.-based supply of advance ceramic powders is an important materials RD&D activity. Currently, U.S. silicon nitride component suppliers are completely dependent on imported powders from Japan and Germany. U.S. companies have relatively little leverage in pricing or availability. Applications of silicon nitride such as bearings and industrial wear-resistant components are growing rapidly. GTE, Dow Chemical, and Ford Motor Company developed high-quality, chemically-derived silicon nitride powders between about 1973 and 1995, but none of these companies are suppliers today.

Large Quantity Scale-up. Scaling up production is a significant step in reducing the cost per part. Implementation of scale up involves high cost and initially a high price to the customer. End users often will not consider the ceramic process until the price-per-part is substantially reduced. *Application development support is needed to accelerate scale-up and cost reduction for high-payoff applications, such as the effort that helped silicon nitride bearings get over the final hurdle and into viable production.*

Increased Automation. Automating a fabrication process can dramatically reduce the costs from labor and increase product yield. Very little automation is integrated into fabrication of advanced structural monolithic ceramics. Ceramic parts must be inspected and measured at multiple points during the process. Automation is difficult and expensive but it can be cost effective. An example is automated manufacturing of ceramic spark plug insulators; approximately three

million spark plugs are produced worldwide per day with high yield and high reliability. *RD&D focused on real production requirements is needed to develop the techniques, process equipment, and instrumentation to perform key fabrication steps (including inspection) in an automated or semi-automated mode.* The U.S. dominance in fabrication process technology has eroded in recent years and a focused research effort is needed to be competitive in the global economy.

Decreased Final Machining. Monolithic ceramics typically require diamond grinding to achieve the final shape and dimensions. Grinding operations are sometimes as expensive as all the other manufacturing steps combined. *Research is needed to improve the grinding process, equipment and tooling to decrease costs, to explore and develop alternate material removal methods; and to fabricate ceramics closer to the final dimensions (near-net-shape fabrication) and thereby minimize the amount of ceramic that must be ground away.*

Lower-Cost Quality Assurance. Quality assurance (QA) of ceramic materials involves in-process and post-process destructive and non-destructive inspections. Many inspection steps at high cost are required to assure that a ceramic component is acceptable for a high-stress structural application. There are many ways to reduce the cost. For example, optimize the process to reduce the number of inspections required. This requires an in-depth understanding of the processing/properties/performance relationships, considerable materials and fabrication RD&D, and property/performance testing feedback. Sometimes, the inspections required can be lowered by a “go/no-go” proof test of the final component. Another way to decrease the cost of QA is to develop lower-cost QA equipment and tests. Advances in the past 10 years in computers, software, and smart sensors offer many opportunities for this approach. *Research is needed to implement strategies for decreasing the costs of QA, including developing automated or semi-automated in-line systems that can make discriminating measurements and judgements quickly and accurately.* This RD&D will need to link with RD&D in materials and processing optimization and component testing.

Rapid Prototyping Integrated into Manufacturing. Tooling and the stages of scale-up of tooling are a significant cost during the transition from prototype fabrication to large-scale manufacturing. Recent advances in rapid prototyping technologies could be used to by-pass some tooling iterations and to produce small quantities of components for end-user evaluation. This could greatly short-cut component development time and cost. *RD&D is needed to demonstrate that rapid prototyping techniques produce components equivalent to those produced by conventional processes, and to integrate rapid prototyping into production-viable processes.*

3. Ceramic Matrix Composites – Challenges and Needs

A ceramic matrix composite (CMC) is a ceramic material that incorporates a reinforcing phase during fabrication. One example of a CMC is mixing particles or whiskers of a ceramic with the matrix ceramic powder and then densifying the mixture using techniques such as sintering or hot pressing. Another example is constructing a preform of long, high-strength ceramic fibers and adding the ceramic matrix by methods such as chemical vapor deposition, sol gel or polymer infiltration, or melt infiltration.

CMCs are being developed to provide an alternative to monolithic ceramics, one with greater toughness that fractures in a non-catastrophic rather than a brittle mode. This has the potential to result in reliable components that end users can use with a level of confidence similar to the one they have for metals. Because CMCs are at a much earlier stage of development than monolithic ceramics, substantial RD&D is needed to realize their full potential, especially those reinforced with continuous fibers. The CMC materials that presently have the best chance of non-brittle failure modes are continuous fiber ceramic composites (CFCCs).

Exhibit 5 lists the key challenges for CMCs (and CFCCs) and the RD&D needed to address these challenges. The challenges and RD&D needs are addressed below. Note: several key CMC challenges are addressed in Section 5 on RD&D needs common to monolithic, composite, and coating ceramics. These efforts need to be integrated with relevant material development, database generation, fabrication, and demonstration activities.

Exhibit 5. Priority RD&D Needs in Ceramic Matrix Composites to Address Key Challenges Faced by Ceramic Manufacturers and End Users

| <i>Key Challenges for CMCs</i> | <i>Priority RD&D Needs to Address the Challenge</i> |
|--|---|
| Reduce the cost of precursors | <ul style="list-style-type: none">• Scale-up/cost reduction of fiber manufacturing• Lower-cost interface materials and deposition processes |
| Improve understanding of failure modes | <ul style="list-style-type: none">• Basic scientific understanding of interactions between CMC constituents and application environments• Micro-and macro-mechanics understanding of interactions of CMC with an applied stress or strain |
| Increase temperature stability to 1200-1500° C | <ul style="list-style-type: none">• Higher-temperature fibers, matrix materials, and interface coatings• Environmental barrier coatings (EBCs)• Active cooling designs |
| Manufacturing scale-up and cost reduction | <ul style="list-style-type: none">• Larger furnace design and construction• Automation/semi-automation of preform fabrication• Low-cost tooling• Near-net-shape fabrication• Low-cost in-process and post-process quality assurance |

Technology Challenge: Reduce the Cost of Precursors

Currently, most of the precursor materials for advanced CFCCs are not in full-scale production (i.e., available only as developmental materials). Consequently, prototypes of CFCC components are expensive. Batch-to-batch variation is a problem because manufacturing controls have not been established. As the technologies evolve, the baseline is continually being replaced by “new and improved” versions, which are generally more expensive. RD&D is needed to better understand the issues and reduce the costs of precursors (i.e., fibers and interface coatings).

RD&D Priority

Scale-up/Cost Reduction of Fiber Manufacturing. Non-oxide fibers cost thousands of dollars per pound. Oxide fibers that have been in the marketplace for years sell for hundreds of dollars per pound because the production volume is still small. The price of fiber is a major barrier, especially for industrial CFCC use. *RD&D to reduce the cost of fiber fabrication and to encourage process scale-up will help break down the cost barrier and accelerate CFCC commercialization.*

Lower-Cost Interface Materials and Deposition Processes. Optimization of the interface or interphase layer between the fibers and matrix is critical to producing a viable CFCC material. Currently, the interface layer is deposited by laboratory techniques that are an expensive step in the fabrication process. *RD&D is needed to reduce the cost of existing deposition methods, develop new cost-effective methods of depositing interface layers, and explore continuous deposition methods rather than batch methods.* As with fiber research, these efforts must be closely integrated with material development, database generation, and demonstration of long-term stability in the use environment.

Technology Challenge: Improve Understanding of Failure Modes

The understanding of CFCC failure modes in several application environments has greatly improved in recent years. However, the basic scientific understanding is still inadequate to assure that CFCC component reliability will meet end-user service requirements.

RD&D Priority

Basic Scientific Understanding of Interactions Between CMC Constituents and Application Environments. The toughening mechanisms for CFCCs are different than for polymer matrix composites, so lessons learned from the many years of use of polymer matrix composites are not directly applicable to CFCCs. The major difference is that a strong bond is desired between the fibers and matrix for a polymer matrix composite, while a relatively weak bond is required for CFCCs. For most CFCCs, this weak bond has been achieved through an interface or interphase layer between the fiber and matrix. To provide long life for the overall composite, the interface layer must be thermodynamically stable so it is not degraded by contact with the matrix, fibers, and any chemical species (such as oxygen, water, alkalis) that might diffuse into the composite or enter through cracks.

At present, interface layers are very sensitive to the high-temperature application environments. *Long term RD&D is needed to understand the various degradation mechanisms of CMCs.* Studies during the past 10 years have demonstrated that fibers and matrix materials degrade in

application environments, and that changes in chemistry (sometimes subtle) can greatly improve stability. Researchers are beginning to understand the mechanisms and find solutions, but further RD&D is needed.

Micro- and Macro-mechanics Understanding of Interactions of CMC with an Applied Stress or Strain. CFCCs (and other CMCs) respond to an applied stress in an application environment in two ways: at the micro-mechanics level (individual reinforcement/matrix interfaces and at crack tips) and at the macro-mechanics level (over the broad composite architecture or structure). *Before engineers can routinely use analytical design models and life prediction models, basic scientific understanding of both micro-mechanics and macro-mechanics is necessary.* Significant progress has been made in recent years, but continued RD&D is necessary.

Technology Challenge: Increase Temperature Stability to 1200-1500° C

Inadequate stability at high temperature is one of the major deficiencies of current CMCs, especially CFCC materials. This applies to both non-oxide and oxide CFCCs and to each composite constituent: fibers, matrix, interface, and surface coatings. Significant improvements have been achieved in the past 5 years. Some CFCC materials have been demonstrated to survive in severe application environments such as a gas turbine engine for about 2500 hours at temperatures in the 1100-1200° C range. However, they have exhibited significant degradation progressing from the surface inward. Environmental barrier coatings (EBCs) applied to the surface have increased the life to over 5000 hours with favorable projections to around 10,000 hours. However, the applications require lifetimes of 20,000 hours or greater. Other applications require higher temperature capability (i.e., in the range of 1200-1500° C).

RD&D Priority

Higher-Temperature Fibers, Matrix Materials, and Interface Coatings. Non-oxide composites such as those containing silicon carbide are not thermodynamically stable in air or high water-vapor atmospheres at high temperature. Efforts during the past couple years to increase the temperature capability of fiber, matrix, and interface materials have yielded some improvement in composite stability. Use of oxide EBCs has provided further improvements in stability and increase in life.

CFCCs based on oxide fibers and matrices also show good potential. These oxide systems are more chemically stable in high temperature and combustion environments than non-oxide ceramics. However, present oxide fibers can only be used at temperatures up to 1100° C in structural applications where significant mechanical stresses are present. The fibers are susceptible to creep deformation at high temperature. Also, the interface layers tend to interact with the fibers or matrix, and the matrix tends to change with time at these temperatures. *RD&D is needed to understand the mechanisms and limitations of both non-oxide and oxide systems and to guide development of improved high-temperature fibers, matrix materials, and interface coatings.* New materials chemistries also need to be explored. Most of the U.S. research has been on simple binary materials such as silicon carbide, aluminum oxide, or silicon nitride. In Europe, they have demonstrated some Si-N-B-O and other compositions that appear to have increased stability at high temperature.

Environmental Barrier Coatings (EBCs). Based on research in the past three years, EBCs are now required to obtain an acceptable component life for SiC-SiC CFCC materials in a gas turbine atmosphere above 1100° C, as well as for non-oxide monolithic turbine components. *On-going efforts on coating composition, refinement of deposition methods, and on long-term testing in realistic application environments need to be continued and extended to higher temperatures.*

Active Cooling Designs. Emphasis in CMCs has been directed at uncooled designs. However, the use temperature cannot exceed the allowable limit for the uncooled CMC. *Research is needed to build active cooling passages into the composite as a design option.* This has the potential to either increase the life of the composite by reducing the temperature to which it is exposed or to allow the composite to be used in a higher temperature application environment. Active cooling for key high temperature applications should be explored.

Technology Challenge: Manufacturing Scale-up and Cost Reduction

The high price of finished CFCC components is a major barrier to many applications. Reducing the cost of precursors, as discussed earlier, is a key step in cost reduction. Increasing the production volume and the scale of manufacturing would also substantially reduce unit costs.

RD&D Priority

Larger Furnace Design and Construction. Furnaces are required to manufacture fibers, to apply coatings to fibers, and to form the ceramic matrix. The term “larger” refers to whatever is needed to allow scale-up of manufacturing and cost reduction. For fiber manufacture and fiber coating, “larger” means equipment and techniques that can throughput an increased number of strands of fiber per unit time. Although study and RD&D are needed, this probably means establishing continuous processes. For adding matrix to fiber preforms, batch processes are necessary for some processes and continuous processes are necessary for others. *Therefore, “larger” can refer to increased furnace size for batch operations and for RD&D to design, build and test continuous furnaces needed for continuous operations.*

Automation/Semi-automation of Preform Fabrication. CFCCs are fabricated by first laying up a preform of coated fibers and then adding the matrix into the preform. Presently, preforms are usually prepared by labor-intensive hand lay-up in a laboratory or job-shop mode. Significant cost reduction and improved reproducibility are possible by integrating automation or semi-automation into preform processes. *RD&D is needed to focus on equipment and tooling design and on evaluation of the resulting CFCC materials (properties) and components (dimensions, reproducibility, and reliability) with the goal of integrating automation or semi-automation of preform fabrication.* Specific areas of RD&D that could provide large benefits include establishing continuous weaving and prepreg lines, cutting or stamping stations, tooling to reduce the time and labor of lay-up, and automated numerically-controlled filament winding.

Low-cost Tooling. CFCC parts require high-temperature tooling (such as graphite) to support the preform during lay-up and early stages of infiltration and densification of the matrix. This tooling is presently expensive and typically can only be used once. *RD&D is needed to find ways to decrease the cost of the tooling, permit multiple use of the tooling, or eliminate some of the tooling.*

Near-Net-Shape Fabrication. Expensive machining and grinding is currently required to achieve the desired dimensional tolerances and surface smoothness of CFCC (and other CMC) components. *RD&D is needed to explore ways of coming closer to the final component requirements during the fabrication process to minimize or eliminate post-process machining or grinding.*

Low-Cost In-process and Post-process Quality Assurance. Quality control inspections and procedures are expensive for CMCs, especially 3D engineered fiber architecture of CFCCs. The major processing defects in CFCC materials are voids or density variations due to inadequate fill of the matrix, irregular fiber distribution, delaminations between composite layers, and cracks. NDE methods such as thermal imaging, ultrasonic scanning, and x-ray radiography (especially CT) have been successful at detecting these types of defects, but are currently labor intensive and expensive. *RD&D is needed to refine NDE techniques so that they can be used in-line for continuous and rapid process control at key stages in the process and post-process.* Achieving this goal will require substantial RD&D in NDE techniques, in equipment development, and in iterations of materials inspection and property evaluation to verify reliability of the NDE equipment and techniques.

4. Ceramic Coating Systems – Challenges and Needs

Ceramic coating systems are defined as an application of ceramic to change the surface of a substrate to

- Enhance specific desired attributes of the substrate and external environment and/or
- Provide a new function.

Coatings are applied and they may or may not be diffused.

Historically, ceramic coatings were developed to impart special properties such as hardness and corrosion resistance to the surface of metals. The metal carries the structural loads, while the ceramic coating provides wear resistance, corrosion resistance, or heat resistance. Major advances have occurred in recent years in the technology of ceramic coating deposition and in the composition of coatings. Whereas early coatings were painted on and fired, coatings are now applied by several different methods: molten particle deposition, physical vapor deposition (sputtering and e-beam), chemical vapor deposition, and reactive methods. Broader use of ceramic coatings is now possible, especially in processing industries with wear and corrosion concerns. Traditional and specialty ceramic coatings are considered a safe, reliable, and usually cost-effective way to gain the benefits of ceramics without the fear of catastrophic failure.

Ceramic coatings have been used for decades in many applications. End-users are comfortable using coated metal to carry structural loads. Consequently, there are less psychological barriers to ceramic coating use compared to monolithic ceramics or CMCs. Because of the high comfort level with traditional ceramic coatings, end users are often not aware of (or motivated to explore) new technologies or potential improvements that could substantially improve the performance and life of ceramic coatings. New and improved coating techniques such as plasma-enhanced chemical vapor deposition, physical vapor deposition, molten particle deposition techniques, and vapor deposition of diamond have widespread potential.

A new challenge for ceramic coatings has been identified in recent years: use ceramic coatings to protect non-oxide monolithic ceramics and CMCs against oxidation and corrosion. Environmental barrier coatings (EBCs) now appear to be required to achieve long life for key high-temperature applications of advanced silicon nitride based ceramics (e.g., gas turbine engines).

Examples of Ceramic Coating Systems

A high-technology ceramic coating that has become increasingly important in gas turbine engines is zirconium oxide. It is used as a thermal barrier coating and allows engines to run considerably hotter by protecting the underlying metal. This extends the component life, increases engine efficiency, and reduces fuel consumption. Continuing RD&D is needed in this area to improve adhesion, prevent attack on the underlying metal by oxygen and chemical impurities in the engine operating environment, and decrease the thermal conductivity of the coating.

One of the most promising new ceramic coating technologies is vapor deposition of diamond, the hardest and most wear-resistant material available. A thin coating of diamond on high-wear surfaces of industrial equipment could save billions of dollars per year on maintenance and replacement. Continuing RD&D is needed to learn how to deposit diamond on a broader range of substrate metals, especially on mild steel.

Exhibit 6 identifies the key coating challenges that are faced by ceramic engineers and end users. The priority RD&D needs to address each challenge are listed. Note: several key coating challenges are addressed in Section 5 on RD&D needs common to monolithic, composite, and coating ceramics. The challenges and RD&D needs are addressed below. These efforts need to be integrated with relevant material development, database generation, fabrication, and demonstration activities.

Exhibit 6. Priority RD&D Needs in Ceramic Coating Systems to Address Key Challenges Faced by Ceramic Manufacturers and End Users

| <i>Key Challenges for Ceramic Coating Systems</i> | <i>Priority RD&D Needs to Address the Challenge</i> |
|--|--|
| Improve coating adhesion to substrate | <ul style="list-style-type: none"> • Improved pre-coating surface treatments • Improved interlayers • Functional gradation |
| Improve understanding of failure modes and mechanisms | <ul style="list-style-type: none"> • Basic scientific understanding • Micro- and macro-mechanics understanding |
| Improve coating and system properties | <ul style="list-style-type: none"> • Improved abrasion resistance to 10 times better than chromium at half the cost • Develop tribological coatings that require minimal liquid lubrication • Develop low-thermal conductivity thermal barrier coatings |

Technology Challenge: Improve Coating Adhesion to the Substrate

The effectiveness and life of a ceramic coating system is often limited by the strength of the coating's bond to the substrate. Improving the control of adhesion and density are essential to innovation in coating processes.

RD&D Priority

Improved Pre-coating Surface Treatments. Pre-coating surface treatments are almost always used to assure that the surface is clean and sometimes textured for improved mechanical adhesion. However, most of these treatments are chemical treatments that have not been updated for many years. Significant improvements are possible in pre-treatments and in the resulting adhesion. *RD&D is needed to systematically explore surface modification processes such as laser, ion beam etching, plasma etching, and ion implantation to determine if significant improvements in adhesion and coating performance can be achieved.*

Improved Interlayers. Some coating systems require interlayers between the substrate and the coating. In some cases, the interlayer has a coefficient of thermal expansion intermediate between the substrate and the coating; this helps to decrease thermal expansion mismatch stresses to acceptable levels. In other cases, the interlayer enhances chemical bonding at the interface or acts as a chemical barrier to decrease diffusion of substances such as oxygen that can degrade the substrate and lead to spalling of the coating. A good example of this latter situation is in the use of zirconium oxide thermal barrier coatings on metal gas turbine engine components. The coatings are porous and the zirconia crystal structure has oxygen vacancies (atom sites where an oxygen ion is missing). Oxygen from the air is able to diffuse through to the metal substrate. An

interlayer material is used to form a barrier to the oxygen. Interlayers are the weak member of most coating systems. If the interlayer could be improved, the life and effectiveness of the coating and the system could be substantially improved. *RD&D is needed to increase the basic understanding of the role and mechanisms of interlayers and to develop interlayers that provide increased adhesion and coating life.*

Functional Gradation. The coating and the material to which it is applied often have dramatically different properties such as different thermal expansion coefficients and elastic modulus. This results in stresses that either crack the coating or cause cracks at or near the coating-substrate interface. Furthermore, coatings and substrates can have radically different chemistries and crystal structures and do not readily form a chemical bond. *RD&D is needed to develop functional gradation to provide a zone near the coating-substrate interface with a graded composition (i.e., between the coating and the substrate).* This provides both chemical and mechanical interlinking of the coating and substrate materials and can potentially result in a large increase in adhesion plus reduction in stresses due to thermal expansion mismatch or elastic mismatch.

Technology Challenge: Improve Understanding of Failure Modes and Mechanisms

An important step in improving the performance and life of a material or system is to thoroughly understand the modes and mechanisms of failure. For a coating system these modes and mechanisms involve interaction of the conditions imposed by the specific application environment (stress, atmosphere, temperature, etc.) with the coating system materials. To obtain a reasonable and useful understanding, RD&D must encompass both bench-scale testing and in-service component testing (such as field kits), materials development, material characterization (pre-test, in-test, and post-test observations and selected property measurements), and analytical model development.

RD&D Priority

Identification of Specific Needs. Collaborative effort is needed with end-users to identify applications where coatings either are not as reliable as desired or where increase in life could provide a major benefit.

Failure Modes and Mechanisms Understanding. Sustained RD&D is needed to better understand the thermochemical interactions of the coating, substrate, and interlayer for selected use environments. RD&D is also needed to understand the micromechanics and macromechanics interactions involving residual stress, applied stress, strain tolerance, and tribological behavior.

Technology Challenge: Improve Coating and System Properties

This broad challenge includes new coating materials development, new and improved coating deposition process development, and improvement in existing coatings and coated components.

RD&D Priority

Improved Abrasion Resistance 10 Times Better Than Chromium at Half the Cost. One promising direction for achieving improved abrasion resistance is to continue RD&D on new materials such as vapor-deposited diamond and diamond-like coatings. These coatings have extremely high hardness and wear resistance. However, their thermal expansion coefficient and

elastic modulus are very different from substrate metals and ceramics. *RD&D is needed to find ways to avoid the resulting cracking and spalling due to thermal expansion and elastic mismatch so that the coatings can be used for a wider range of substrates and applications. RD&D are also needed to find ways to apply the coatings at lower temperature onto diverse substrates.*

Develop Tribological Coatings That Require Minimal Liquid Lubrication. Many applications that involve sliding surfaces could benefit from a higher-temperature operation, but liquid lubricants can not survive high temperatures. Other applications could benefit from reducing the amount of liquid lubrication required because of design problems in delivering liquid lubricant to the sliding interface, pollution emitted by degradation or burning of the lubricant, and other factors. In general, ceramic surfaces are less reactive than metal surfaces and are less prone to adhesive wear. Also, ceramics can be polished to a high surface finish that minimizes friction. *RD&D is needed to develop improved tribological coatings that require minimal lubrication, such as with solid lubrication, where a constituent of the ceramic provides self-lubrication as the ceramic slowly wears.*

Develop Low-Thermal Conductivity Thermal Barrier Coatings. Thermal barrier coatings based on zirconium oxide ceramics are standard in aircraft gas turbine engines and are now being integrated into industrial gas turbine engines. The coating allows the engine to operate at much higher temperatures than the metals alone can survive, resulting in substantial improvement in the efficiency and specific power of the engine. Although extensive RD&D has been conducted since the 1970s, significant improvements are possible by increasing the life and reliability of the coated components, improving the adhesion and oxidation resistance, and reducing the thermal conductivity. Further reduction in thermal conductivity, especially with a goal of reaching one-fourth the thermal conductivity of current coatings, is a difficult challenge and will require continued high-priority RD&D.

5. Challenges and Needs Common to Monolithic Ceramics, Ceramic Matrix Composites, and Ceramic Coating Systems

Some challenges in the development of ceramic-based materials for advanced applications are common to monolithic ceramics, CMCs, and ceramic coatings systems. These are listed in Exhibit 7. The challenges and RD&D needs are addressed below. These efforts need to be integrated with relevant material development, database generation, fabrication, and demonstration activities.

Exhibit 7. Challenges and Priority RD&D Needs Common to Monolithic Ceramics, CMCs, and Ceramic Coating Systems

| <i>Key Challenges Common to Advanced Ceramics</i> | <i>Priority RD&D Needs to Address the Challenge</i> |
|--|---|
| Long-term testing and validation in application environments | <ul style="list-style-type: none">• Viable laboratory simulation tests• Long-term monitored field tests |
| Design and life prediction methods and tools | <ul style="list-style-type: none">• Improved standards and databases• Design manuals and database handbooks• Data relevant to application needs• Experimental validation of computational models• Integration of design and manufacturing (concurrent design) |
| Improve Attachment | <ul style="list-style-type: none">• Low-stress attachment techniques |
| On-site repair | <ul style="list-style-type: none">• Patching and other repair technologies |
| Education and training | <ul style="list-style-type: none">• Compilation of success stories• Seminars, workshops, and presentations at trade shows and professional society meetings• Improved education/training within the ceramics industry• Study of market sectors to identify high-payoff opportunities; education of end-users to show how the ceramics can provide these payoffs. |

Technology Challenge: Long-Term Testing and Validation in Application Environments

End-users are comfortable selecting metal components for an application based upon property data and limited trials but require additional proof for ceramic components. This proof includes extensive study and long-term test results from actual field tests. These efforts are expensive, require long-term commitment by the supplier and the end-user, and often require a couple of design iterations before the component is successful. Even if the potential payoff is very large, time and risk factors often dissuade the end-user from considering a ceramic as a solution. To foster commercialization, stakeholders must work together to achieve a level of field demonstration that ensures end-user confidence when selecting a ceramic.

RD&D Priority

Viable Laboratory Simulation Tests. A priority RD&D need is designing, constructing, and validating laboratory test facilities that provide adequate simulation of selected application environments. These facilities need to be integrated into application evaluation efforts, component design efforts, and materials development efforts. The following example illustrates the essential role of simulated tests. In turbine engine studies of monolithic silicon nitride and SiC/SiC CFCC materials, laboratory simulation tests that closely duplicated the application environment were necessary because property tests indicated much longer life than was demonstrated in the engine tests. Engine conditions produced an environment leading to a failure mode that had not been encountered in the laboratory. After the failure mechanism was identified by cutup and evaluation of engine hardware, a laboratory test that better simulated the engine conditions was established. This dramatically accelerated number of tests that could be conducted and the number of controlled variants that could be evaluated, which rapidly improved the life of CFCC materials.

Long-Term Monitored Field Tests. Field testing is needed to identify critical failure modes and mechanisms in candidate ceramic components, guide RD&D to quickly achieve solutions, and build end-user confidence that ceramics can be reliable. Field test demonstrations involving successful partnerships between ceramic material suppliers, OEMs, end-users, and the government have been essential to the advancement of ceramic materials into critical applications.

Technology Challenge: Design and Life Prediction Methods and Tools

End-users are comfortable designing with metals. They have handbooks filled with data generated with standardized tests and analytical models for both design and life prediction that have been verified through years of use. Similar models, databases and verified experience need to be established so end users will be comfortable designing with ceramic materials.

RD&D Priority

Improved Standards and Databases. American Society for Testing of Materials (ASTM) now has comprehensive test standards for monolithic ceramics and for some characteristics of coatings. Key tests for CMCs are being validated. Developing the database is more challenging because materials are evolving faster than a detailed database can be generated, especially for advanced materials such as silicon nitride and CFCCs. *To improve standards and databases, a systematic effort needs to continue to select key materials for property measurements and to conduct the measurements necessary for material qualification and component design.*

Design Manuals and Database Handbooks. As standards become established, databases generated, and design/life prediction models developed and experimentally verified, user-friendly design manuals and data handbooks need to be compiled. For example, the first edition of MIL Handbook 17 on CMCs needs to be completed and upgraded regularly as CMC technologies evolve. Comparable handbooks need to be prepared for monolithic ceramics and ceramic coatings. User-friendly manuals and handbooks need to be compiled for industrial design engineers.

Data Relevant to Application Needs. Physical, thermal, and mechanical property data are important for initial analytical design and long-term data on the survival of the material under the

real application environments (stress, cycles, chemical, etc.) are necessary for life prediction. Property data acquisition needs to be closely linked to exposure of the ceramic materials in real and simulated application environments through a combination of test coupons and cutup of actual components. RD&D is needed to generate data to evaluate the needs in specific applications.

Experimental Validation of Computational Models. *Computational models need to be upgraded as more data are generated and evaluated and the models need to be experimentally validated.* This will foster better applied science and technology understanding that will permit more analytical design and less experimental validation in the future. As a result, end users will be able to select from available ceramics with confidence.

Integration of Design and Manufacturing (Concurrent Design). Historically, advanced ceramic designs have not been integrated with manufacturing considerations. Often a component successfully designed to work in an application was then deemed too expensive to use because of manufacturing difficulties. Manufacturing considerations need to be an integral part of the design process, and materials suppliers need to be a part of the design team. The goal is a component design that can be manufactured at a viable cost. *RD&D is needed to develop concurrent design capability that can be used to evaluate a ceramic-based material for an advanced application.* A longer-term goal is to integrate rapid prototype fabrication technologies into initial prototypes and seamlessly transition these technologies into production manufacturing.

Technology Challenge: Improve Attachment

Ceramics often fail at the point of attachment because of their brittle behavior and inability to redistribute stress away from points of contact. Ceramic coatings are often used so the component can be attached at the underlying metal. The attachment needs are an important consideration during the initial design, but the data needed to do this is inadequate.

RD&D Priority

Low-stress Attachment Techniques. Long-term research is needed to better understand attachment issues so that refined design guidelines can be developed to reduce the stress and help decision-makers select the correct ceramic-based material versus other materials. Additional RD&D is needed to improve the effectiveness of joining technologies that are necessary when components cannot be fabricated as a single piece because of cost, manufacturing considerations, or stress.

Technology Challenge: On-Site Repair

Currently, most ceramic components cannot be repaired on-site. Off-site repairs pose significant costs when components fail.

RD&D Priority

Patching and Other Repair Technologies. Research is needed to determine if on-site repair or patching is feasible and beneficial.

Technology Challenge: Education and Training

Perception of OEMs and end-users that ceramics are not reliable is a major deterrent to broader use of ceramics. Sometimes these perceptions are correct, but in most cases new advanced ceramics can reliably meet the application requirements and greatly increase component life and performance. Increased efforts on education and training are needed to break down the negative perceptions.

Priority

Compilation of Success Stories. Compile written documentation of success stories to illustrate the benefits of advanced ceramics and disseminate them to appropriate OEMs and end-users.

Seminars, Workshops, and Presentations at Trade Shows and Professional Society Meetings. Prepare articles for trade journals that update advanced ceramics capabilities and include the success stories. Provide seminars, workshops, and presentations at trade shows and society meetings. Continue to have a booth at trade shows that focuses on use of advanced materials.

Improved Education/Training within the Ceramics Industry. Establish textbooks and curriculum for a specialization and degree in advanced ceramics engineering. Upgrade the training of engineers to include up-to-date content on advanced ceramic materials to more broadly establish the understanding that advanced ceramics are an option to solving engineering challenges. Establish continuing education for engineers whose applications might benefit from ceramics.

Study of Market Sectors to Identify High-Payoff Opportunities; Education of End-users to Show How the Ceramics Can Provide these Payoffs. OEMs and end-users need more than education. They need to be part of a partnership to analyze potential solutions to their problems. Study contracts to bring the key parties together is an important first step.

Appendix A: Agenda from the Roadmapping Workshop

Creating a Technology Roadmap for Advanced Ceramics – Charting Our Course

| Time | Session | Location |
|--------------------------------------|---|----------------------------------|
| Wednesday, September 22, 1999 | | |
| 8:00 - 10:00 | Registration and Coffee | Concorde Foyer A |
| 10:00 - 12:00 | Plenary Session <ol style="list-style-type: none"> 1. <i>Introduction</i> by Mr. David Bennett, Chairman of USACA, Dow Corning Corporation 2. <i>An Overview of Advanced Ceramics Markets</i> – keynote presentation by Dr. Thomas Abraham, Business Communication, Inc. 3. <i>Advanced Structural Ceramics Vision 2020</i> – William H. Werst, Executive Director of USACA 4. <i>Overview of the Facilitated Process and Instructions</i> – Jack Eisenhower, Energetics, Inc. | Concorde A |
| 12:00 – 1:00 | Lunch | Atrium |
| 1:00 - 5:00 | Breakout Sessions <ul style="list-style-type: none"> • Monolithic Ceramics • Ceramic Composites • Advanced Ceramic Coatings | Clipper Concorde A Fairfax |
| 6:00 - 7:00 | Reception | Earhart/Lindbergh |
| 7:00 - 9:00 | Dinner | Earhart/Lindbergh |
| Thursday, September 23, 1999 | | |
| 7:00 - 8:00 | Continental Breakfast | Atrium |
| 8:00 - 12:00 | Breakout Sessions – <i>Continued</i> | |
| 12:00 - 1:00 | Lunch | Atrium |
| 1:00 - 3:00 | Summary Session Findings of Breakout Sessions and Closing Comments | Concorde A |
| 3:00 | Adjourn | |

Appendix B: Workshop Participants

Thomas Abraham
Director, Advanced Materials Group
Editor, High Tech Ceramics News
Business Communications Co., Inc.
25 Van Zant Street
Norwalk, CT 06855
Tel: 203-853-4266
Fax: 203-853-0348
Email: tombcc@aol.com

Clare Allocca
Program Manager of Advanced Materials
National Institute of Standards and Technology
100 Bureau Drive Stop 4730 Building 101 Room
A225
Gaithersburg, MD 20899
Tel: 301-975-4359
Fax: 301-548-1087
Email: clare.allocca@nist.gov

Kenneth Anderson
Ferro Corporation
453 W. McConreySt
Shreve, OH 44676
Tel: 330-567-2145 x8268
Fax:
Email: andersonk@ferro.com

David Bennett
Director, Cooperative Research & Development
Dow Corning Corporation
Suite 600 1133 Connecticut Avenue, NW
Washington, DC 20036
Tel: 202-785-0585
Fax: 202-785-0421
Email: dave.bennett@dowcorning.com

Bruce Boardman
Manager, Metals Research
Deere & Company
Technical Center 3300 River Drive
Moline, IL 61265-1746
Tel: 309-765-3814
Fax: 309-765-3807
Email: bb14725@deere.com

Richard Brent
Director of Government Affairs
Caterpillar Inc./Solar Turbines, Inc.
818 Connecticut Avenue, NW, Suite 600
Washington, DC 20006-2702
Tel: 202-293-4327
Fax: 202-293-4336
Email: solardc@bellatlantic.net

Jerry Brockmeyer
Director
Ultramet, Inc.
12173 Montague Street
Pacoima, CA 91331
Tel: 818-899-0236
Fax: 818-890-1946
Email: jerry.brockmeyer@ultramet.com

Tom Carstensen
Sikorsky Aircraft
6900 Main Street P.O.Box 9729
Stratford, CT 06615
Tel: 203-386-4717
Fax:
Email: tcarstensen@sikorsky.com

R.G. Clinton
National Aeronautics and Space Administration
NASA Marshall Space Center
Huntsville, AL 35512
Tel: 256-544-2682
Fax: 256-544-2825
Email: corky.clinton@msfc.nasa.gov

Phillip Craig
Account Manager
Honeywell Advanced Composites, Inc.
Diamond State Industrial Park
400 Bellevue Road
Newark, DE 19713
Tel: 302-631-1303
Fax: 302-631-1320
Email: phil.craig@honeywell.com

Stanley Dapkunas
Program Manager
National Institute of Standards and Technology
100 Bureau Drive, A256/223 Mail Stop 8520
Gaithersburg, MD 20899
Tel: 301-975-6119
Fax: 301-975-5334
Email: stanley.dapkunas@NIST.gov

Michael Effinger
NASA Marshall Space Flight Center
ED 34
Huntsville, AL 35812
Tel: 256-544-5637
Email: mike.effinger@msfc.nasa.gov

Melissa Eichner
Energetics, Incorporated
7164 Gateway Drive
Columbia, MD 21046
Tel: 410-953-6234
Fax: 410-290-0377
Email: meichner@energetics.com

Jack Eisenhauer
Energetics, Incorporated
7164 Gateway Drive
Columbia, MD 21046
Tel: 410-290-0370
Fax: 410-290-0377
Email: jeisenhauer@energetics.com

Richard Engdahl
President
Amercom/Synterials, Inc.
318 Victory Drive
Herndon, VA 20170
Tel: 703-471-9310
Fax: 703-435-0374
Email: ree@wizard.net

Tom Foltz
Textron Systems Corporation
201 Lowell Street Mailstop 1103
Wilmington, MA 01887
Tel: 978-657-3310
Fax: 978-657-2930
Email: tfoltz@systems.textron.com

Cheryl Francis
Marion Composites
150 Johnston Road
Marion, VA 24354
Tel: 540-783-3121 x1336
Fax: 540-783-9666
Email: cfrancis@mcomposites.com

Stephen Freiman
Chief, Ceramics Division
National Institute of Standards and Technology
100 Bureau Drive, Room A256 Building 223
Mailstop 8520
Gaithersburg, MD 20899
Tel: 301-975-6119
Fax:
Email: stephen.freiman@NIST.gov

Douglas Freitag
Dow Corning Corporation Consultant
Dow Corning Corporation
21150 New Hampshire Ave.
Brookville, MD 20833-1938
Tel: 301-570-3821
Fax: 301-570-3836
Email: dfreitag@ix.netcom.com

Hans Friedericy
Director, Research and Technology
AlliedSignal Aerospace
Suite, 700 South 1001 Penn. Avenue, N.W.
Washington, DC 20004
Tel: 202-662-2638
Fax: 202-662-2621
Email: hans.friedericy@alliedsignal.com

Deborah Haught
Program Manager
U.S. Department of Energy
Room 5F-064 1000 Indep. Avenue, SW
Washington, DC 20585
Tel: 202-586-2211
Fax: 202-586-1658
Email: Debbie.Haught@ee.doe.gov

Peter Heitman
Section Chief, Advanced Materials
Rolls-Royce Allison
PO Box 420
Indianapolis, IN 46206-0420
Tel: 317-230-3803
Fax: 317-230-2866
Email: peter.w.heitman@allison.com

John Holowczak
United Technologies Research Center
411 Silver Lane
E. Hartford, CT 06108
Tel: 860-610-1649
Fax:
Email: holowcje@utrc.utc.com

Keith Jamison
Energetics, Incorporated
7164 Gateway Drive
Columbia, MD 21046
Tel: 410-290-0370
Fax: 410-290-0377
Email: kjamison@energetics.com

D. Ray Johnson
Manager, Propulsion Materials
Oak Ridge National Laboratory
P.O. Box 2008
No. 1 Bethel Valley Road
Oak Ridge, TN 37831-6066
Tel: 865-576-6832
Fax: 865-574-6098
Email: johnsondr@ornl.gov

Jill Jonkouski
Program Manager
U.S. Department of Energy
9800 South Cass Avenue Building 201
Argonne, IL 60439
Tel: 630-252-2657
Fax: 630-252-8649
Email: jill.jonkouski@ch.doe.gov

Michael Karnitz
Manager, Industrial Technologies Program
Oak Ridge National Laboratory
Building 4515 PO Box 2008, MS-6065
Oak Ridge, TN 37831-6065
Tel: 865-574-5150
Fax: 865-241-0411
Email: karnitzma@ornl.gov

Michael Kelley
Government Affairs Manager
Advanced Refractory Technologies, Inc.
c/o Berkshire Inc. 7800 Foxhound Road
McLean, VA 22102
Tel: 703-821-3179
Fax: 703-448-3515
Email: N/A

Ronald Kelley
President
Strategic Partners, Inc.
Suite 1000 S 601 13th Street, N.W.
Washington, DC 20005-3807
Tel: 202-256-5211
Fax: 202-661-2299
Email: ronkelley@aol.com

John Koenig
Southern Research Institute
757 Tom Martin Drive
P.O.Box 55305
Birmingham, AL 35211
Tel: 205-581-2436
Fax: 205-581-2414
Email: koenig@sri.org

Edwin Kraft
General Manager, Operations
Kyocera Industrial Ceramics Corporation
Advanced Ceramic Technology Center
5713 East Fourth Plain Blvd.
Vancouver, WA 98661-6857
Tel: 360-750-6147
Fax: 360-750-6215
Email: ed.kraft@kyocera.com

Stanley Levine
Chief, Ceramic Branch
NASA Glen Research Center
M/S 106/5 21000 Brookpark Road
Cleveland, OH 44135
Tel: 216-433-3276
Fax: 216-433-5544
Email: slevine@grc.nasa.gov

Robert Licht
Manager, Government Programs Group
Saint-Gobain Ceramics & Plastics, Inc.
Goddard Road
Northboro, MA 01532
Tel: 508-351-7815
Fax: 508-351-7760
Email: robert.h.licht@sgcna.com

Krishan Luthra
Manager, Thermal & Structural Ceramic
General Electric Corporate Research & Development
Building K1, Room 3B4 One Research Circle
Niskayona, NY 12309
Tel: 518-387-6348
Fax: 518-387-7563
Email: luthra@crd.ge.com

Janet Lynch
General Electric Company
Suite 1100 1299 Pennsylvania Avenue, NW
Washington, DC 20004
Tel: 202-637-4052
Fax: 202-637-4412
Email: janet.lynch@corporate.ge.com

Michael Lynn
Business Manager
3M
Building 207-1W-11 3M Center
St. Paul, MN 55144-1000
Tel: 651-736-9682
Fax: 651-736-1237
Email: mmlynn@mmm.com

Tim Marth
Global Business Manager
Surface Treatment Technologies
Saint-Gobain/Norton Pakco Industrial Ceramics
55 Hill View Avenue
Latrobe, PA 15650
Tel: 724-539-6033
Fax: 724-539-6070
Email: tmarth@nortonpakco.com

James McCauley
US Army Research Laboratory
Attn: AMSRL-WM-MC Weapons & Materials
Aberdeen Proving Ground
Aberdeen, MD 21005-5069
Tel: 410-306-0711
Fax:
Email: mccauley@arl.mil

Richard Montano
American Scientific Materials Technologies
Company
485 Madison Avenue 24th Floor
New York, NY 10022
Tel: 212-702-9849
Fax: 212-758-0832
Email: richardmontano@worldnet.ATT.net

Harry Morehead
Manager, New Program Development
Siemens Westinghouse Power Corporation
MS 381 4400 Alafaya Trail
Orlando, FL 32829
Tel: 407-281-3322
Fax: 407-281-5014
Email: harry.morehead@swpc.siemens.com

Jay Morrison
Siemens Westinghouse Power Corporation
MC 303 4400 Alafaya Trail
Orlando, FL 32829
Tel: 407-249-7381
Fax:
Email: jay.morrison@swpc.siemens.com

Joel Moskowitz
President & CEO
Ceradyne, Inc
3169 Red Hill Avenue
Costa Mesa, CA 92626
Tel: 714-549-0421 x261
Fax: 714-549-5787
Email: jmoskowitz@ceradyne.com

Tracy Murphy
American Scientific Materials Technologies Company
485 Madison Avenue Floor 24
New York, NY 10022
Tel: 212-702-9849
Fax: 212-758-0832
Email: tmurphy@astm.to

Michael Readey
Program Manager, Ceramic Technology
Caterpillar Inc./Solar Turbines, Inc.
Caterpillar Technology Center, Building E
P.O.Box 1875
Peoria, IL 61656-1875
Tel: 309-578-6742
Fax: 309-578-2953
Email: Readey_Michael_J@cat.com

Gopal Revankar
Staff Metallurgist
Deere & Company
3300 River Drive
Moline, IL 61265
Tel: 309-765-3795
Fax: 309-765-3807
Email: gr54758@deere.com

David Richerson
Principal
Richerson & Associates
2093 E. Delmont Drive
Salt Lake City, UT 84117
Tel: 801-272-0436
Fax: 801-272-2423
Email: richersond@aol.com

David Shanahan
V.P. and General Manager
COI Ceramics, Inc.
9617 Distribution Avenue
San Diego, CA 92121
Tel: 858-621-7452
Fax: 858-621-7451
Email: dshanahan@enqceramics.com

Merrill Smith
Program Manager
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585-0121
Tel: 202-586-3646
Fax: 202-586-1658
Email: merrill.smith@ee.doe.gov

Andrew Szweda
Director of New Business Power Generation
COI Ceramics, Inc.
9617 Distribution Avenue
San Diego, CA 92121
Tel: 858-621-7463
Fax: 858-621-7451
Email: aszweda@coiceramics.com

Robert Tucker
Praxair Surface Technologies, Inc.
P.O.Box 24184 1500 Polco Street
Indianapolis, IN 46224
Tel: 317-240-2539
Fax: 317-240-2464
Email: rtucker@geof.psti.praxair.com

Mark Van Roode
Product Manager
Caterpillar Inc./Solar Turbines, Inc.
Mail Zone C-2 P.O. Box 85376
San Diego, CA 92186-5376
Tel: 619-544-5549
Fax: 619-544-5378
Email: van_roode_mark_x@solarturbines.com

Richard Wagner
McDermott Technology
P.O.Box 11165
Lynchburg, VA 24506
Tel: 804-522-5697
Fax:
Email: rich.a.wagner@mcdermott.com

Appendix C: Detailed Vision for 2020

In 2020, advanced structural ceramics will be a cost-effective, preferred material for industrial, military, aerospace, transportation, consumer product, and other applications. Advanced ceramic visions are presented below for materials, fabrication, design, environment, health and safety, education, and markets. These visions establish ambitious goals for advanced structural ceramics and help identify the RD&D priorities necessary to achieve them.

Materials Vision: A wide variety of ceramic materials are available with unique properties that exceed the performance of alternative materials, meet customer needs, and provide enhanced design options.

- High-purity **raw materials** in a wide variety of forms are available at 25 percent below 1999 costs and with **higher yields**, approaching 100 percent.
- Better **computational** materials science- and knowledge-based engineering tools are available to increase prediction accuracy and accelerate development of new, low-cost, multifunctional materials.
- **Reliability** exceeds alternative materials.
- **Standards** with available underlying test methods are established for all types of advanced ceramics.
- Suppliers provide **parts that exceed the value** of alternative materials in terms of cost, performance, and cycle time.
- **Product life** is equivalent or superior to alternative materials.
- Materials have environmental resistance and foreign object damage (FOD) tolerance.
- **Reliable attachment** approaches are incorporated into design practices.
- **Temperature capability** is 400 ° to 500 °C higher than 1999 materials with equal life.
- Design and process advancements provide 100 percent **predictability and controllability**.
- Time from concept to market is less than 6 months.
- **Fiber interface coatings and coating processes** increase density and adhesion and decrease costs.
- **Composite costs** are not more than twice that of metals in high-temperature niche applications and equivalent in cost for general applications.
- **SiC fibers** are one-tenth of 1999 costs for high-temperature applications and reach 3200 °F.
- Consolidation and raw material improvements double the **weibul moduli**.

Fabrication Vision: Fabricated parts with advanced monoliths, composites, and coating systems are preferred to alternative materials due to superior cost, performance, cycle time, and yield.

- **Finished parts** are produced with yields approaching 100 percent (i.e., less scrap) at 25 percent of 1999 costs and 20 percent of 1999 cycle times.
- **Prototype and small volume parts** are routinely produced cost-effectively with a one-week turnaround.
- **Promising Laboratory** processes of 1999 are transitioned to full-scale manufacturing.
- **Batch** processing is used less as large-scale production increases.
- **Semicontinuous and continuous** processes are available for use as appropriate.
- **Repair and joining** processes are used to increase yields (i.e., in-service NDE), provide in-service maintenance, and construct large structures.
- Low-energy **coating processes** permit the control of density and adhesion.
- **Part finishing** is automated, cost-effective, minimized to keep costs down, and eliminated whenever possible.
- **Non-destructive evaluation techniques** for identifying flawed parts in-process are commonplace, utilized at multiple points in the manufacturing process, and generally interactive with automated process controls.

- **Quality assurance** is enhanced by traceability and eliminating steps.
- **Dimensional and surface finishing control** eliminates defects and post-process inspection.
- Pre-forming and part consolidation are highly automated, efficient, and near-net shape.
- Coating equipment and coating process design tools are easy to use and available with low capital and operational costs.
- **Remanufacturing** is used to repair and refurbish parts.
- The use of **semi-skilled labor** reduces labor costs.
- **Ceramic supplier base** is strengthened and expanded by consolidation, integration, and alliances.

Design Vision: Advanced ceramics are seen as viable alternatives to traditional materials in diverse applications. Products are designed with ceramic materials from the start, not just as replacements or repairs.

- **Design tools** are readily available to design engineers, enabling efficient incorporation of advanced ceramics in machines and devices. The engineers, in turn, are confident in the end-use performance of these systems.
- **Standards** exist for commonly used advanced ceramics, and their properties are listed in design handbooks and computer-aided design tools.

Environment, Health, and Safety Vision: Advanced ceramics are viewed as energy-efficient, safe, environmentally benign, and clean and exceed environmental and energy efficiency standards.

- **Ceramic plants** are safe, clean, energy-efficient, and environmentally benign.
- **Hazardous chemical** use is reduced by 75 percent.
- **Emissions** from ceramic fabrication processes are reduced by 90 percent versus the 1999 average.
- **Worker safety** is maximized and the workplace environment is healthy and clean, indicated by no OSHA incidents.
- Parts **operate safely** in commercial applications.
- Ceramic parts make a significant contribution to helping industry and other consumers achieve their **energy-efficiency and emissions-reductions** goals (e.g., in turbine and internal combustion engines and in industries such as aluminum, glass, and semiconductors).
- After-market **disassembly and recycling** services differentiate ceramic suppliers.

Education: Advanced ceramics are widely used in part and product design due to effective education of teachers, workers, customers, designers, government, and political leaders. Everyone understands that ceramic materials improve performance, reduce energy consumption, and improve reliability of finished products.

- **Courses** are routinely taught in engineering materials classes such that all graduating materials and mechanical engineers are confident designing systems incorporating ceramic materials.
- Educational programs exist to **train industry workers** in the proper techniques for fabricating and evaluating components.
- Programs to **educate existing engineers** on designing with advanced ceramics are readily available in a variety of modern media, including Internet, DVD, classroom, virtual reality, and video classrooms.
- Formal training programs exist to **educate customers**.

Markets: Advanced ceramics are the preferred material for applications requiring high-temperature resistance, corrosion resistance, wear resistance, and light weight. Marketing efforts will focus on new and/or expanded applications in the following areas:

- ***Power generation and fuel cells***
- ***Turbine engines*** (hot and wear zones)
- ***Aerospace and military*** (civilian and military structural parts and propulsion systems)
- ***Industrial process equipment*** (heat exchangers, radiant burners, furnace fans, hot fixtures)
- ***Sensors and shields*** (coatings, sleeves, and piezoelectric devices to measure process temperatures, pressures, and other critical parameters)
- ***Filtration and cleanup devices*** for harsh environments (hot gas filters, catalytic converters)
- ***Automotive applications*** including high-performance and hybrid propulsion vehicles (catalytic converters, spark plugs, sensors, wear sleeves, thermal barrier coatings, and flywheel engines/brakes)
- ***Large internal combustion engines*** (valves, followers, bearings, sleeves)
- ***Heavy equipment*** (agriculture and mining)
- ***Biomedical***
- ***Cutting tools***
- ***Structural electronics***
- ***Micromachines***
- ***Consumer-based markets***
- ***Paper***
- ***Aluminum***
- ***Mining***

Appendix D: Workshop Results – RD&D Needs for Monolithic Ceramics

A comprehensive list of RD&D needs for monolithic ceramics is presented in Exhibit 8. The RD&D areas – materials development, materials database, design and life prediction, non-destructive evaluation, fabrication optimization, and demonstration – are discussed below. Improving cost-effectiveness, while not always stated, is a need in each area.

Materials Development

The RD&D needed to improve the material properties of monolithic ceramics include efforts to: improve the understanding of material characteristics versus application failure modes; increase resistance to fracture (higher toughness, strength, resistance to impact and contact stress); increase resistance to wear and corrosion; improve tribology, develop higher temperature capabilities in application environments; and increase material reliability.

Materials Database

Adequate monolithic ceramic property data, necessary for designing ceramic components for advanced structural applications, is often unavailable. Handbooks comparable to those for metals do not exist, and often test methods and standards are deficient. RD&D is needed to establish a design database comparable to that of metals. This includes procedures for affordable data generation.

Design and Life Prediction

As computers become more powerful, they could aid in the faster, more efficient introduction of advanced materials into structural applications through the use of analytical design tools, rather than through “make and break” iterations. Design and life prediction methods and models need to be developed and verified and these user-friendly hardware and software tools made available to materials suppliers, OEMs, and end users.

Non-destructive Evaluation

Monolithic ceramics fracture when an applied mechanical or thermal stress concentrates at a tiny defect inside the microstructure of the ceramic. For highly stressed structural applications, defects that lead to fracture can be tiny, as small as 50 micrometers (0.002 inch). Small defects are difficult to detect by non-destructive evaluation techniques, especially by low-cost techniques. Research efforts need to expand to develop cost-effective NDE techniques. The long-range goal is to establish NDE techniques that decrease inspection costs to 5 percent of the total manufacturing cost; currently, inspection costs can often be more than 20 percent. Since NDE is an integral part of the fabrication/manufacturing process, additional NDE RD&D needs are addressed in the Fabrication section below.

Fabrication Optimization

The nature and quality of the monolithic ceramic fabrication process determines key properties, material reliability, and shapes that can be produced. Thus, there is substantial overlap of fabrication research needs with needs in other areas. RD&D must continue to improve starting materials (powders and other precursors), as well as refine each step in the fabrication process. This includes incorporating sensors and other NDE tools to ensure repeatability of each process step in order to yield consistent, reliable monolithic ceramic parts. Monolithic ceramics such as silicon nitride already offer significant benefits but at a cost that is too high for many applications. RD&D will help decrease the cost of precursors, reduce the cost and/or amount of machining and NDE required, integrate rapid prototyping into manufacturing, increase automation, and scale up manufacturing operations.

Demonstrations

In general, laboratory testing does not adequately simulate real-world application environments and conditions. Field tests have dramatically demonstrated the importance of testing actual components in real application environments in order to identify in-use failure modes and mechanisms, as well as guide the RD&D addressing material and design deficiencies.

Exhibit 8. Monolithic Ceramics RD&D Needs

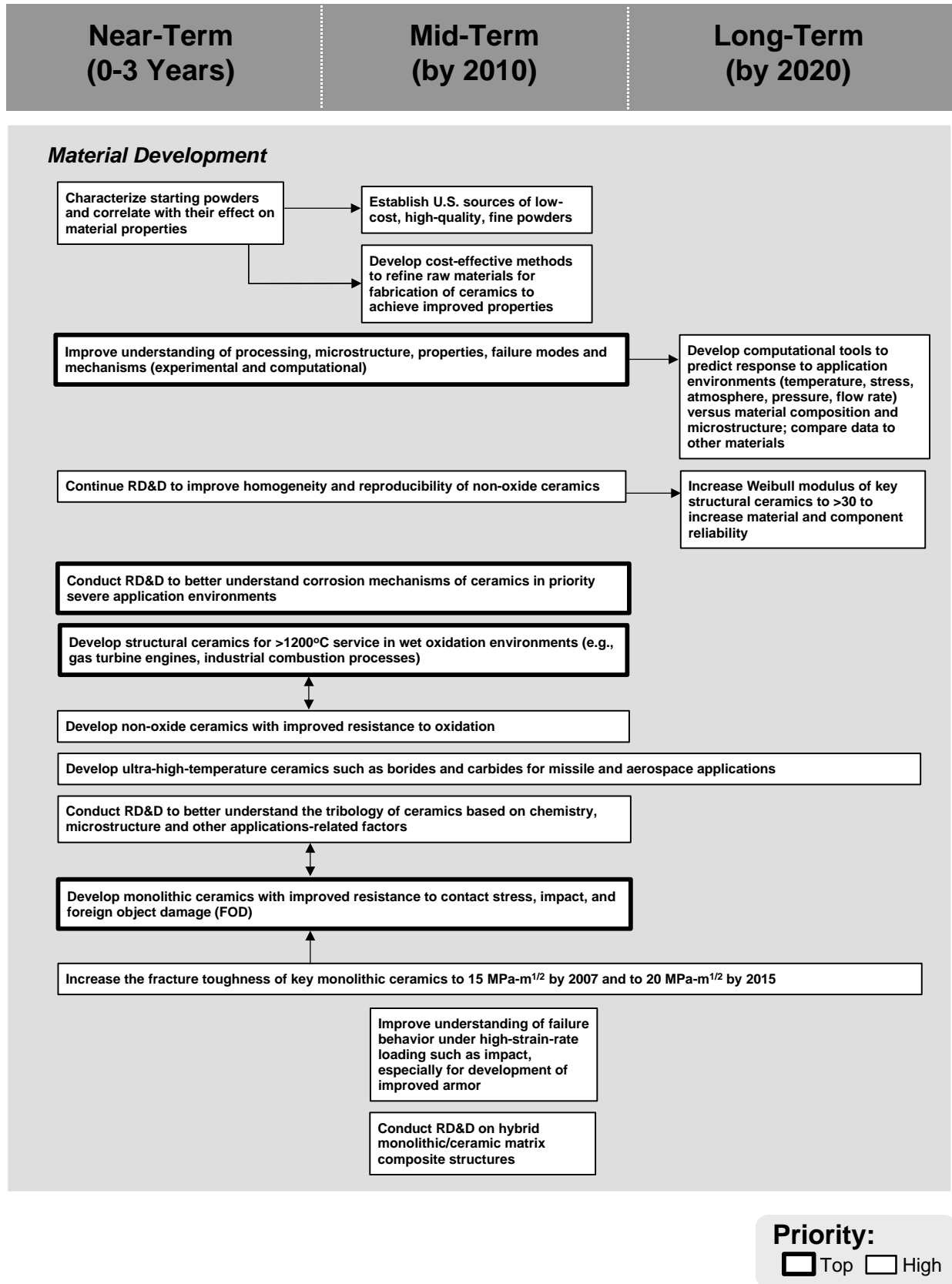
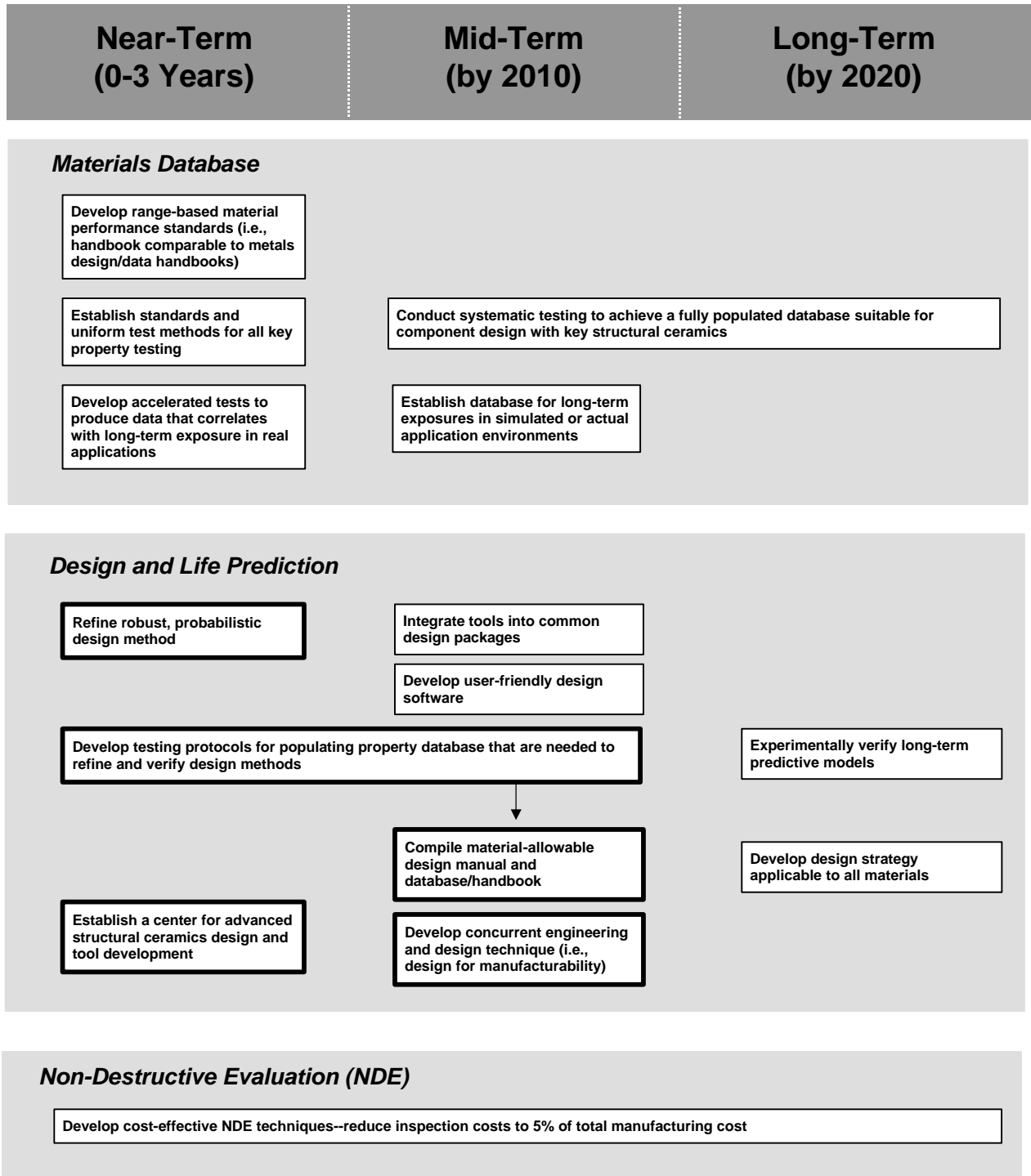


Exhibit 8. Monolithic Ceramics RD&D Needs *(continued)*



Priority:

☒ Top ☐ High

Exhibit 8. Monolithic Ceramics RD&D Needs *(continued)*

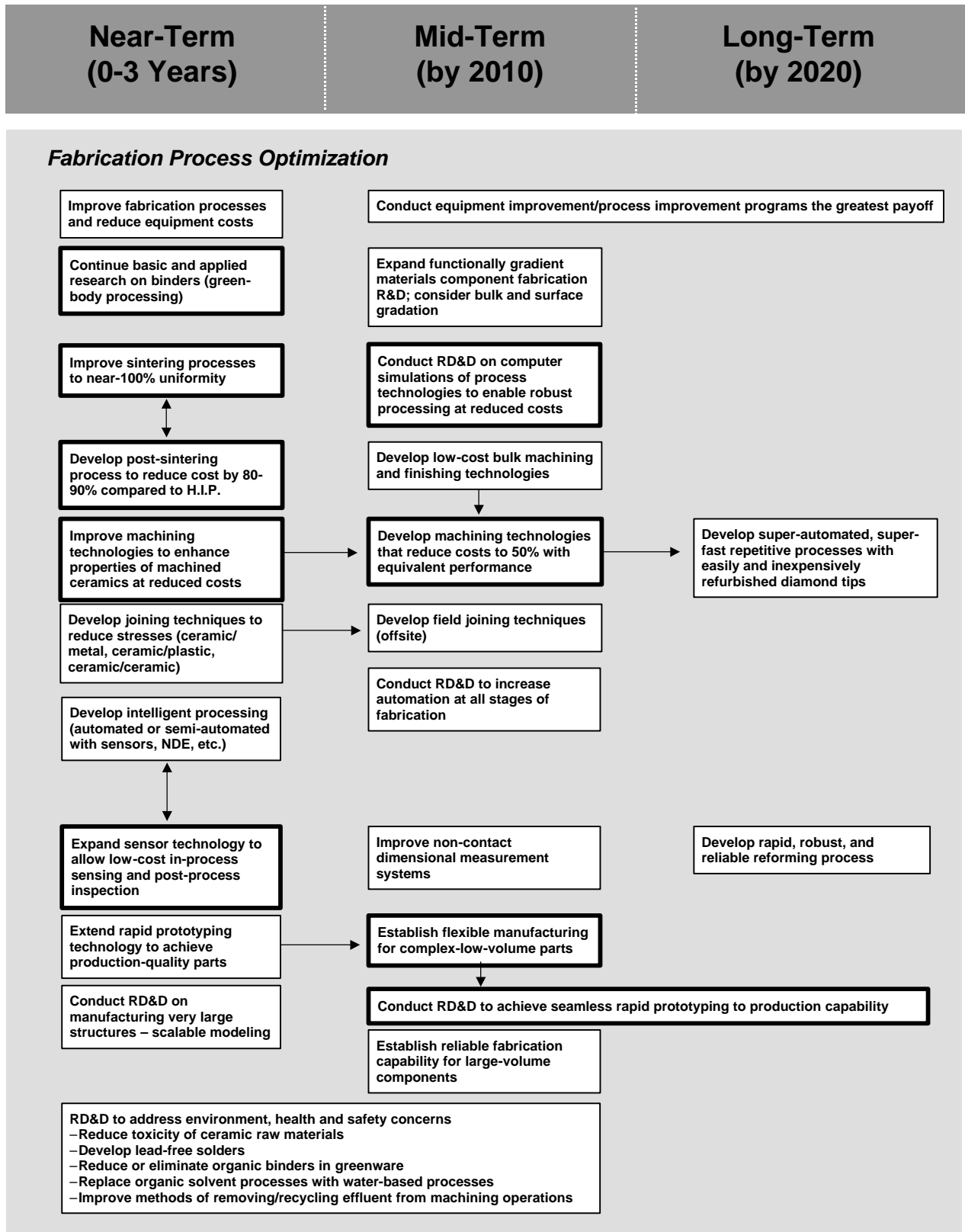


Exhibit 8. Monolithic Ceramics RD&D Needs *(continued)*

| Near-Term (0-3 Years) | Mid-Term (by 2010) | Long-Term (by 2020) |
|--------------------------|-----------------------|------------------------|
|--------------------------|-----------------------|------------------------|

Demonstration

Develop application-specific testing protocols that includes extensive field testing to bolster end-user confidence in monolithic ceramics and to encourage suppliers to fabricate enough parts to guide cost reduction efforts

Priority:

☒ Top ☐ High

Appendix E: Workshop Results – RD&D Needs for Ceramic Matrix Composites

A comprehensive list of RD&D needs for CMCs is presented in Exhibit 9. The key RD&D areas – materials RD&D, materials database, design and life prediction, non-destructive evaluation, fabrication, and demonstration – are discussed below. Improving cost-effectiveness, while not always stated, is a need in each area.

Materials Development

A continuous fiber composite ceramic (CFCC) is a complex CMC material consisting of high-strength ceramic fibers in a ceramic matrix, an interface coating between the fibers and matrix, and often a ceramic coating to seal the surface of the composite from degradation. Because the technology is still in its early stages, RD&D is needed to gain a scientific understanding of the interrelationship of the fibers, matrix and coatings to each other, to properties, and to interaction with application environments, as well as to explore failure modes and mechanisms, and to improve/optimize the CMC materials. There is also a priority need to increase the high-temperature capability of CMC materials. Current CMC materials are showing resilience at temperatures of up to 1100-1200°C, but longer life at these and even higher temperatures is necessary for many key applications.

Materials Database

The database for CMC materials is small compared to that of metals or even monolithic ceramics. Substantial RD&D is needed to establish standardized tests and to create and analyze a database suitable for supporting material development and component design. Because CMCs are especially sensitive to application environments, property measurements must be conducted either in the application environment or a close simulation. Obtaining this data will present a major challenge.

Design and Life Prediction

Ceramic matrix composites are highly directional structures that require a special design and life prediction methodology. Existing models for polymer matrix composites provide a starting point but require substantial modification because of the different failure modes and mechanisms of CMCs. Before reliable design and life prediction models can be established, extensive CMC fabrication and testing must be conducted to gain a fundamental scientific understanding of factors such as micromechanics and macromechanics of interaction of the composite with an applied stress and thermochemical interactions with key application environments. Thus, there must be close coordination between efforts to establish models and other efforts on CMC materials development, fabrication development, database generation, and application demonstrations.

Non-Destructive Evaluation

NDE techniques are needed for in-line process control, for post-process inspection (especially to detect insipient failure and remaining life), and for rapid or in-line inspection of components in application service.

Fabrication Optimization

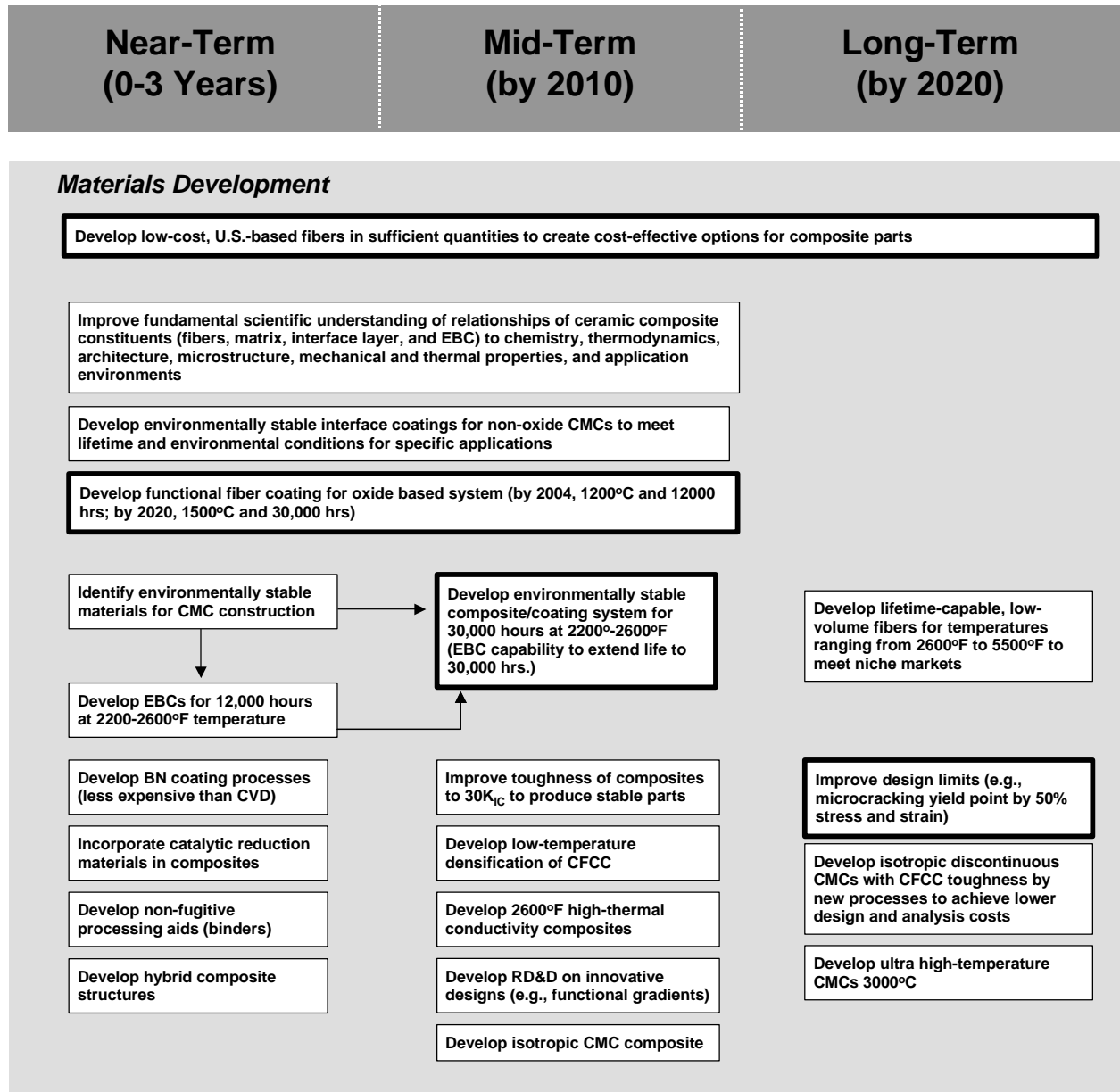
CFCCs are important because of their potential high reliability and ability to avoid catastrophic failures. RD&D needs include: refinement/reproducibility of the fabrication process (e.g., NDE for quality assurance); cost reduction of both starting materials (especially fibers) and each step in the fabrication process; and scale-up of key fabrication processes to a capability suitable for meeting the application needs of industry and other sectors. RD&D is needed to focus on fabrication scale-up and cost reduction as well as demonstration of the resulting CFCC components in substantial field testing.

Demonstrations

Demonstration programs are important for CMCs for several reasons. First, CMCs have not existed long enough to establish an adequate success base to encourage OEMs and end users to select them for an application. Demonstration programs that subsidize design and procurement of the CMC components and their installation into equipment are often the best way to encourage OEMs or end users to consider such a new material. Second, the current prototype level of CMC fabrication capability results in high cost per part, another barrier to OEM or end user willingness to consider CMCs. Third, the early stage of technology development requires careful monitoring of prototype parts before, during and after testing, thus creating a need for special programmatic procedures and instrumentation.

Prior efforts have verified that testing CMC materials in real environments is critical. Demonstration programs conducted in actual equipment at a field test site or at a company test facility provide the best feedback on both design and material issues for CMCs. However, since most applications demand tens of thousands of hours of life, achieving lifetime data takes a long time and requires multiple test sites. An additional need is to develop laboratory simulation tests that correlate with long-term site tests, especially accelerated simulation tests.

Exhibit 9. Ceramic Matrix Composites RD&D Needs



Priority:

☒ Top ☐ High

Exhibit 9. Ceramic Matrix Composites RD&D Needs *(continued)*

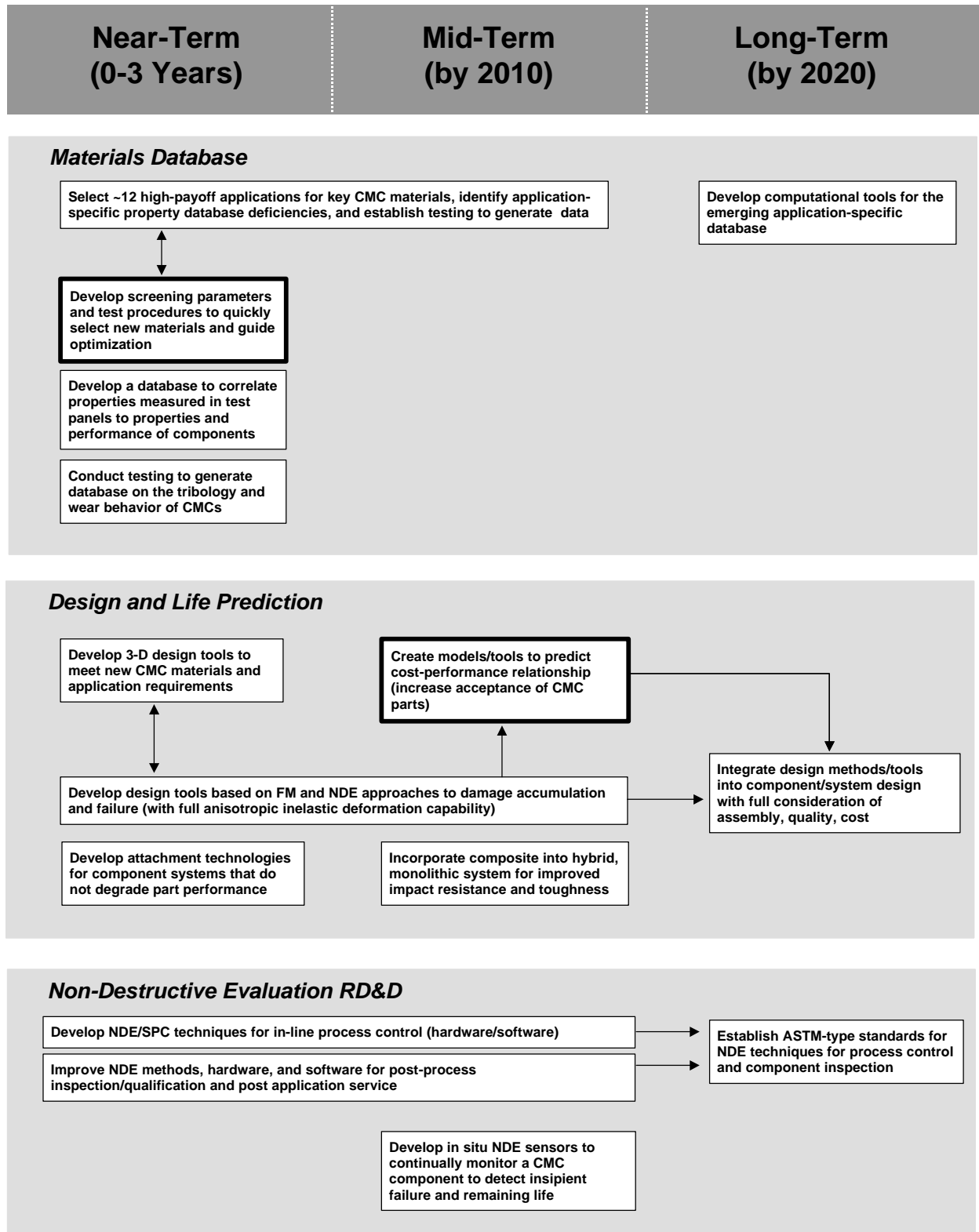


Exhibit 9. Ceramic Matrix Composites RD&D Needs *(continued)*

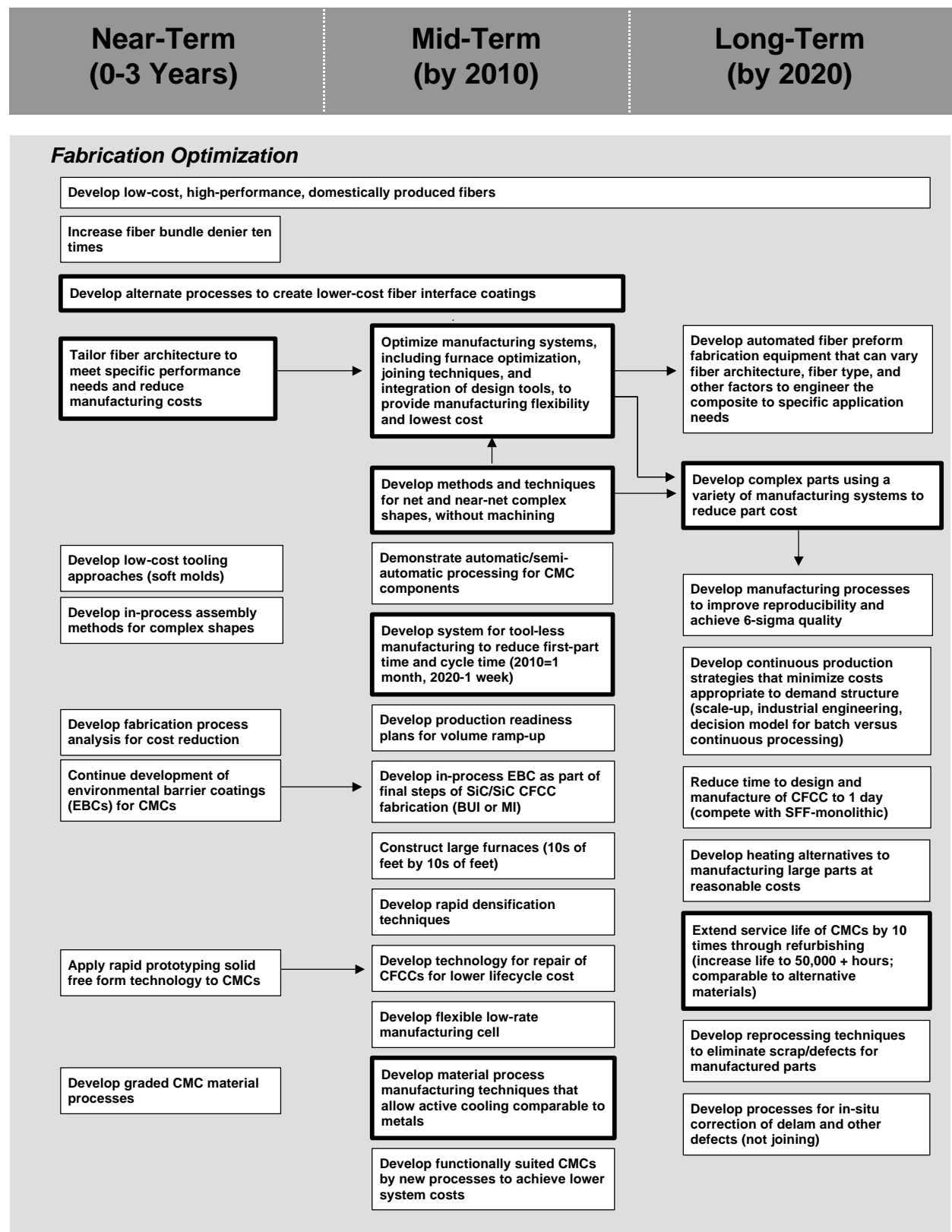
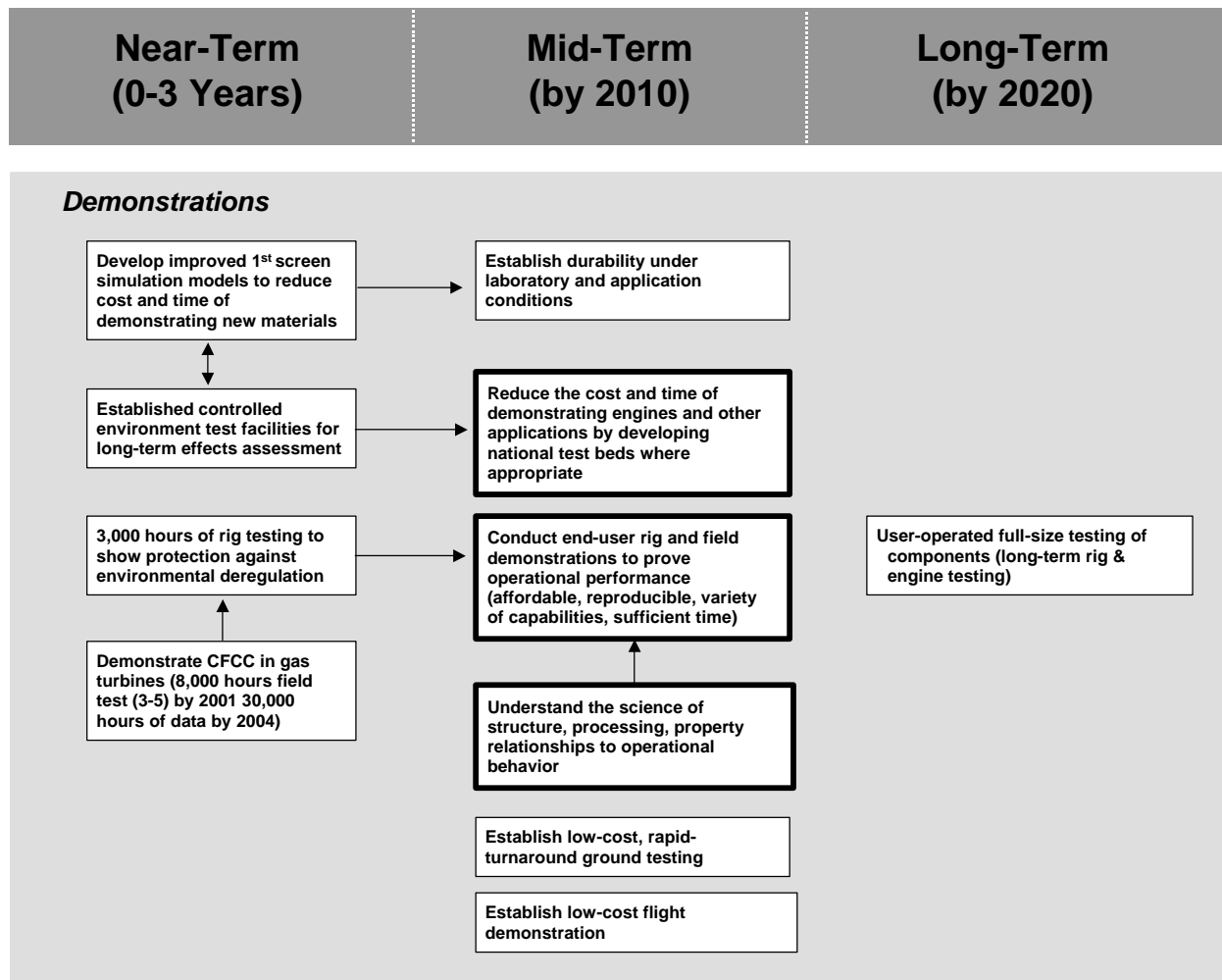


Exhibit 9. Ceramic Matrix Composites RD&D Needs *(continued)*



Appendix F: Workshop Results – RD&D Needs for Ceramic Coating Systems

A comprehensive list of RD&D needs for ceramic coating systems is presented in Exhibit 10. The key RD&D areas – materials development, materials database, design and life prediction, non-destructive evaluation, fabrication optimization, and demonstration – are discussed below. Improving cost-effectiveness, while not always stated, is also a need in each area.

Materials Development

The priority RD&D needs for materials include improving scientific understanding of coating attributes versus coating performance in applications, increasing coating adhesion, developing ceramic coating systems with superior abrasion resistance and tribology characteristics, developing coating systems with improved corrosion resistance and temperature capability, and increasing the high-temperature capability and reducing the thermal conductivity of thermal barrier coatings.

Coating Systems Database

In order to choose whether to use a coating, monolithic ceramic, or CMC, an OEM or end user needs a suitable database to consult. RD&D is needed to establish a coating systems database. RD&D is also needed to develop standard test methods for coatings that provide information on application performance in applications as well as help to establish a basic scientific understanding of composition/processing/properties/ performance relationships. The ultimate goal is to develop an accessible database that can be readily and easily used for material selection and component design.

Design and Life Prediction

Considerable research has been conducted in recent years to develop analytical design and life prediction methods for monolithic ceramics and CMCs, yet little has been done for ceramic coatings. As the use of thermal barrier, environmental barrier, and wear-resistant coatings expands to meet increasingly severe application conditions or to extend component life in existing applications, efforts to establish better design and life prediction capabilities must be stepped up. Specifically, models based on first principles and measurable properties need to be developed that correlate with performance.

Non-Destructive Evaluation

Quality assurance of coatings presents a variety of challenges, including strength and reliability of adhesion, uniformity of thickness, microstructure features such as porosity and grain size, and the general properties of the coating. Given the advances that have occurred in recent years in instrumentation and NDE, NDE should be able to be integrated into the coating process to continuously monitor these issues and ensure consistent coating quality.

Fabrication Optimization

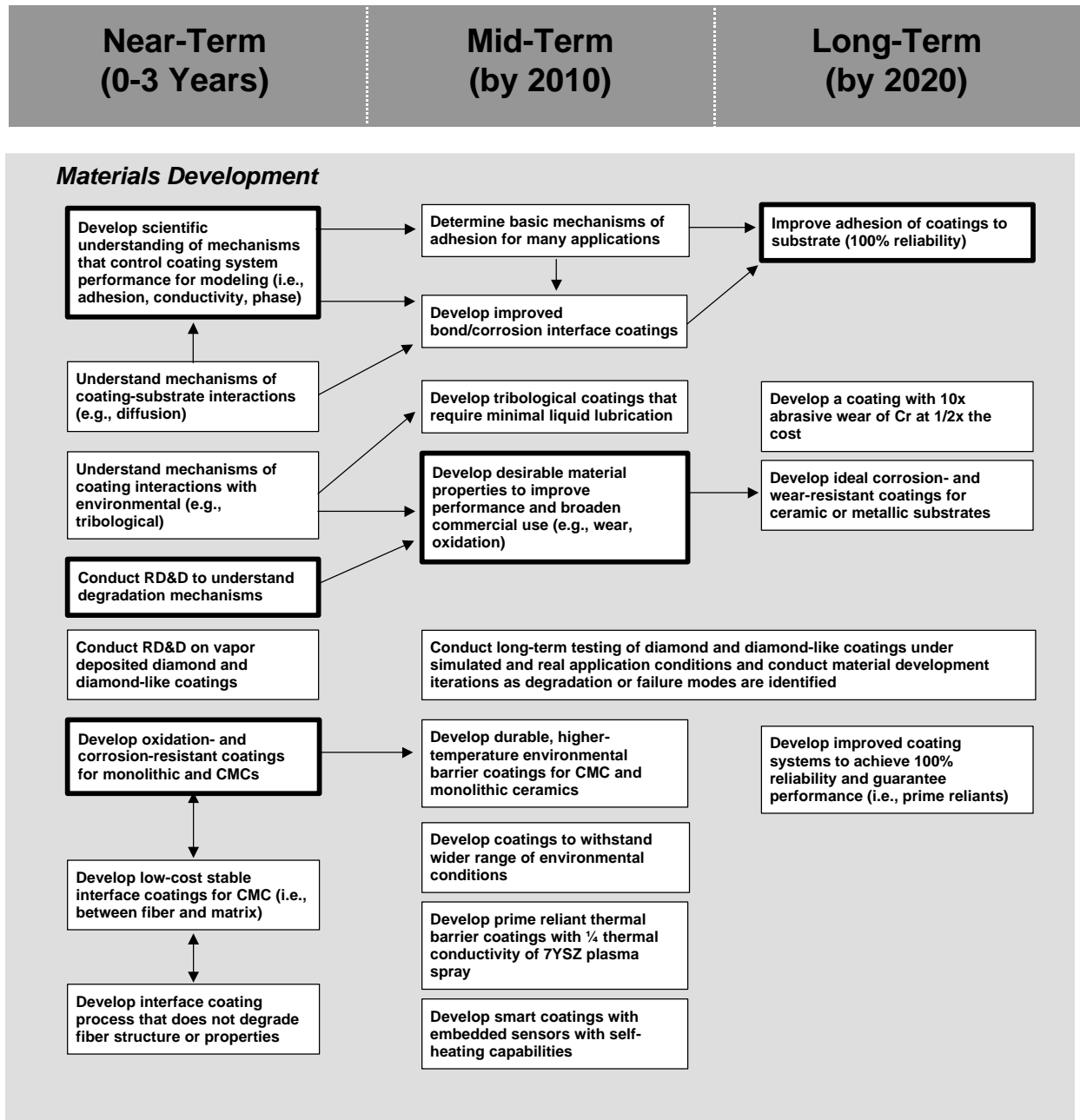
RD&D is needed to improve coating system fabrication. The goals are to increase coating quality and reproducibility, and integrate modeling and on-line NDE into the fabrication process, while ultimately decreasing cost by 40 to 75 percent (depending on the specific coating process). Achieving these goals will require improvements in precursor materials, in each step of the fabrication process, and in equipment design/function.

Demonstrations

Although end users are usually more willing to try a ceramic-coated metal than a monolithic ceramic or a CMC, they are still hesitant to do a trial evaluation. As with other ceramic-based materials, a successful

trial usually requires several iterations of design, material, or both. An effective approach is an *insertion program* -- a partnership among the supplier, the component designer (often an OEM), the end user, and the government (as a catalyst). Such a program is a logical outcome of successful RD&D efforts in coating materials development, design, and fabrication. The outcome of an insertion demonstration program is multifold: working relationships are developed among the supplier, OEM, and end user; end users gain confidence that the ceramic will be reliable and beneficial; and suppliers accumulate enough fabrication experience during field testing to initiate a viable, cost-effective manufacturing process.

Exhibit 10. Coating Systems RD&D Needs



Priority:
☒ Top ☐ High

Exhibit 10. Coating Systems RD&D Needs *(continued)*

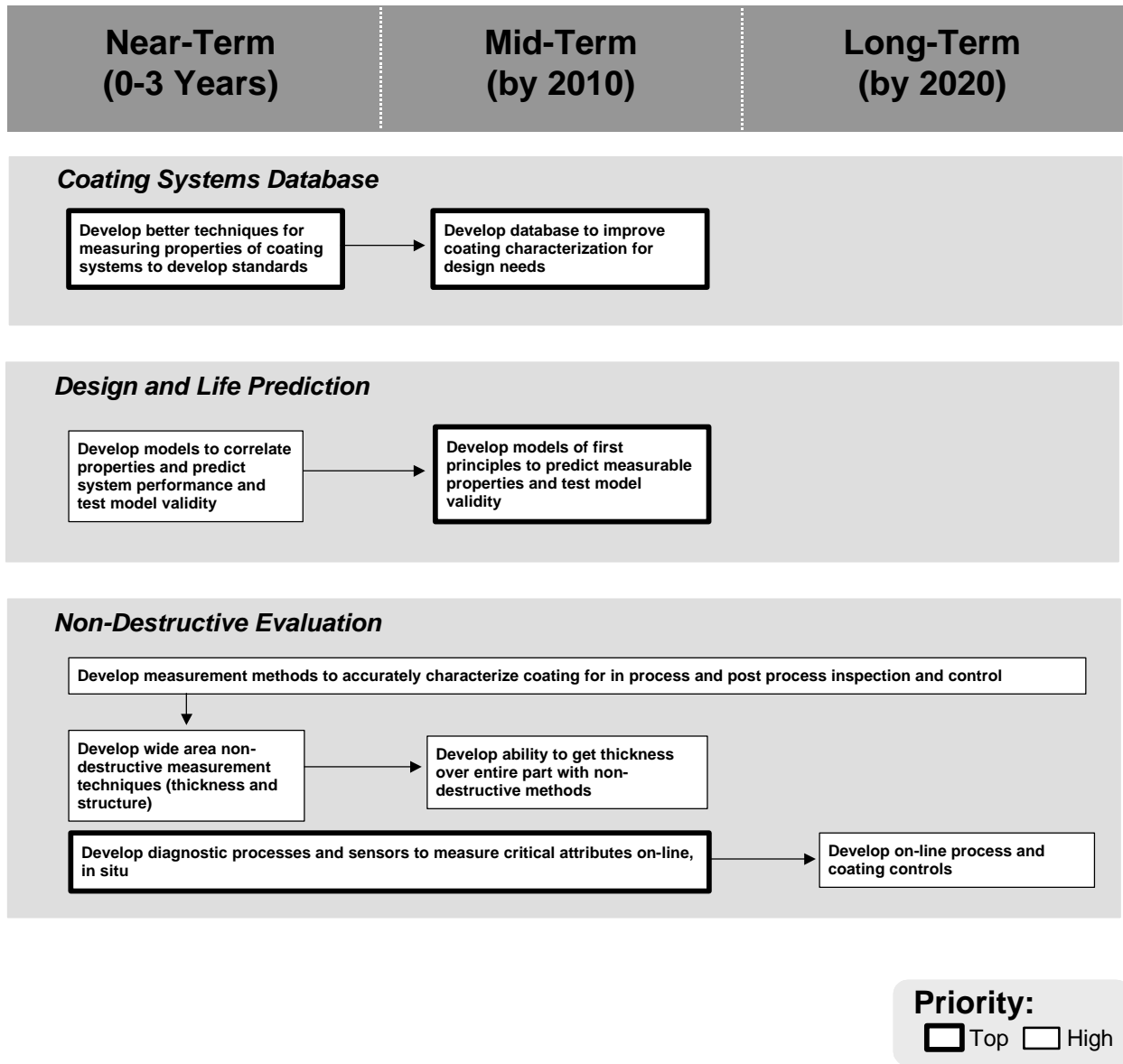
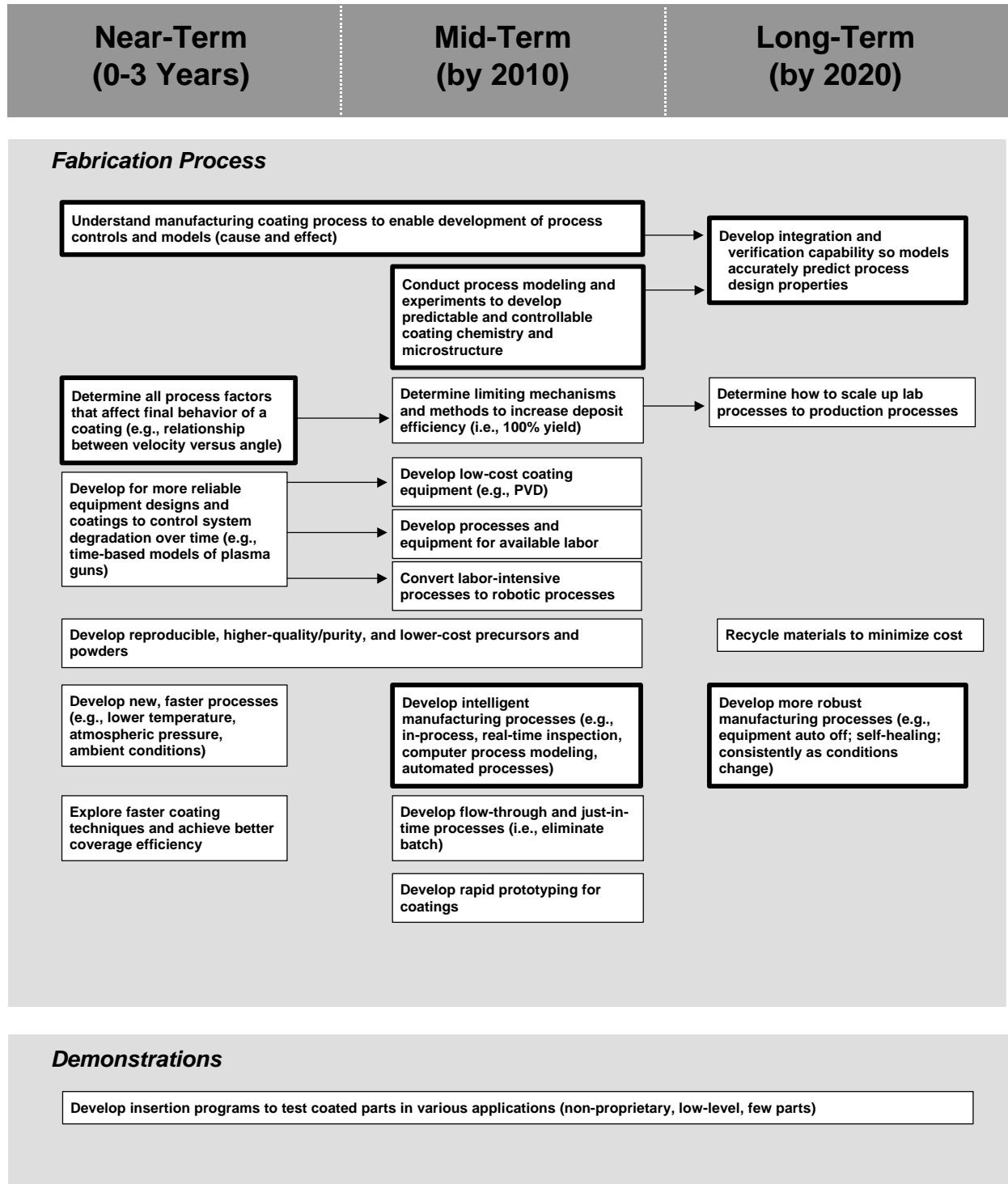


Exhibit 10. Coating Systems RD&D Needs *(continued)*



Priority:
☒ Top ☐ High